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Water footprint of winter wheat under climate change: Trends and uncertainties associated to the ensemble of crop models

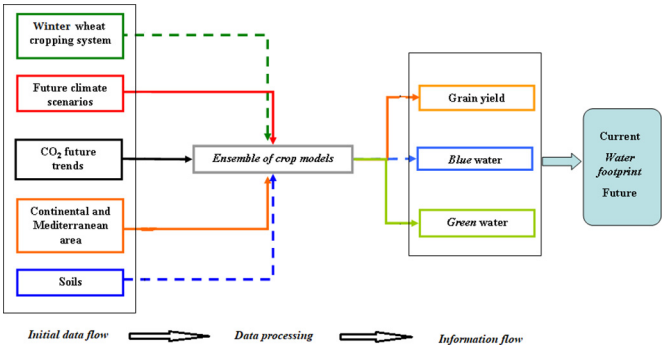
Pasquale Garofalo [a,*], Domenico Ventrella [a], Kurt Christian Kersebaum [b], Anne Gobin [c], Miroslav Trnka [d], Luisa Giglio [a], Martin Dubrovský [d], Mirko Castellini [a]

[a] Council for Agricultural Research and Economics, Research Center for Agriculture and Environment (CREA-AA), Via Celso Ulpiani 5, 70125 Bari, Italy
[b] Leibniz Centre for Agricultural Landscape Research (ZALF), D-15374 Müncheberg, Germany
[c] Flemish Institute for Technological Research (VITO), B-2400 Mol, Belgium
[d] Global Change Research Institute (CzechGlobe), 603 00 Brno, Czech Republic

HIGHLIGHTS

- An ensemble of crop models was applied to assess the wheat water footprint (*WF*) in two European climate areas;
- The effects of 5 Global Circulation Models and 2 CO_2 concentrations on rainfed and irrigated crops were assessed;
- Grain yield would remain the same in Mediterranean area or even improved in Continental area;
- Further improvements of *WF* would be expected under irrigated management.

GRAPHICAL ABSTRACT



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ABSTRACT

The impact of climate change could undermine the future grain production as a consequence of increased temperature and drought condition or improve the crop performance owing to the increased CO_2 in the atmosphere. Wheat water demand and yield are strictly related to climate conditions of the area where the plants are cropped. In this study, we assessed the future trends of grain yield and water consumption in two European regions, Germany (Continental region) and Italy (Mediterranean region) in the light of the multiple sources of uncertainty related to climate and yield forecasts. Four crop models were set up under combinations of two European climate regions, five Global Circulation Models and two Representative CO_2 Concentration Pathways, 486 ppm and 540 ppm in 2050. Yield and water use were assessed under rainfed and irrigated regimes, and the water footprint of green water and total water was estimated. Our results indicated that projected yields were comparable (Mediterranean area) or even improved (+9%; Continental area) in rainfed conditions in comparison to the current trend; and water supply enhanced crop performance (+22% in Germany and +19% in Italy, as mean). Crop water consumption (both green and blue) remained stable in future projections but the water footprint was 5% lower on average in Italy and 23% in Germany when compared to the baseline. Despite the uncertainty in future predictions related to the factors analysed, our result indicated that current wheat production and its water footprint could become more favourable under climate change.

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* Corresponding author.
E-mail address: pasquale.garofalo@crea.gov.it (P. Garofalo).

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1. Introduction

The current cropping systems are often managed to reach high performances rates, but this could negatively impact the environment, contributing to land degradation, pollution and depletion of natural resources (Soussana, 2014). Among natural resources exploitation, agricultural systems account for about 85% of global freshwater consumption, with a main contribution of irrigation that is responsible for 70% of total freshwater withdrawal (Ridoutt et al., 2009; Lamastra et al., 2014).

An indicator that relates yield to the consumption of water resources is the "Water Footprint" which was introduced by Hoekstra (2003, 2008). Crop production is strictly dependent on evapotranspiration (Stanhill, 1986; Sinclair et al., 1984), thus the Water Footprint of a crop (*WF*) is defined as the volume of water (directly) consumed for its production. Green and blue water stand for the evapotranspirated water coming from rain and irrigation water, respectively (Siebert and Döll, 2010). In this context, decreases in water availability can negatively affect crop yield, which is further compromised when water scarcity is associated with adverse weather events related to rainfall amount and seasonal distribution (Trnka et al., 2011; Gobin et al., 2017).

The IPCC Assessment Reports (IPCC, 2014) relate an increase in global temperature from 1996 to 2005 to higher Green House Gases (GHG) emissions into the atmosphere. The projections for future climate in Mediterranean areas (Giorgi and Lionello, 2008) showed a decrease in rainfall from −11% in the winter months to −34% in the summer months, and a surface warming from +3.1 °C for the winter months to +4.9 °C for the summer months. Moreover, Mediterranean projections show that dry periods might begin earlier, last longer and become more intensive, according to A1B scenario for the last two decades of this century (Aguilera et al., 2015). In Continental Europe, the temperature is expected to increase by up to 3–4 °C in summer, while precipitation is projected to increase by up to 10%, mainly in winter. In the Boreal zone of Europe, temperatures would increase, during the winter period with 4–7 °C, and yearly precipitation with up to 40%.Extreme events such as storms, floods and droughts with drier and hotter summers are projected to become more harmful in the Temperate Oceanic zone (Lindner et al., 2010).

The Mediterranean region could be a possible hotspot for decades to come, as a consequence of increasing temperatures and changes in frequency and amount of rainfall, with strong impacts on agricultural production (Saadi et al., 2015). However, the negative implications reported above, may be compensated by positive effects of increasing atmospheric CO_2 concentration, in particular for C3 plants, such as wheat and many other agricultural crops (Ventrella et al., 2012b). In addition, crop response to climatic drivers strongly depends on the environment and characteristics of the cultivation area (Wassenaar et al., 1999).

In this context, *WF* can be considered as an aggregate and multidimensional indicator of water use, because it quantifies the different types of water consumption as a result of different growing drivers in space and time. *WF* is different from the concept of a water balance, the latter describing the difference between fluxes in and out from the system. In contrast, the *WF* includes different types of water, namely rainfall (green water; *GW*) and water from pollution by human activities (grey water), and water consumption through irrigation from other sources (blue water; *BW*) insofar as water is returned to its source (Lamastra et al., 2014). The assessment of *GW* and *BW* for a specific cropping system or a specific crop is the main way to define the virtual water flows from the area where the crop is cultivated to the region where the crop is processed or consumed (Hoekstra et al., 2011). In addition to the direct consumption of water due to the evapotranspiration process, *WF* can also include indirect water consumption, e.g. the water used for producing materials applied in the field. In Life Cycle Assessment (*LCA*) studies (Niero, 2015), the analysis of crop water consumption can have a regionalized approach and extend to water flows coming from rivers, lakes or other natural resources. Issues on the estimation of the *WF* are raised because of the contrasting effects of climatic variables (single or in interaction with each other) affecting the water consumption and crop yield especially under future climate change scenarios (Huang et al., 2018).

The combined effect of simulation models, site characteristics, climate models, projected atmospheric CO_2 concentration and other added variables, makes future projections highly uncertain (Godfray et al., 2010; Asseng et al., 2013). Recent studies have shown that ensembles of simulations constitutes a methodological framework to assess the uncertainty of estimation of climate impact on crop growth (Palosuo et al., 2011; Martre et al., 2015) and water consumption (Cammarano et al., 2016). Additionally, climate impacts on crop production, water consumption and *WF* will help improve the overall understanding in the light of future policy making. The ranking and importance of different sources of uncertainty will become an essential milestone for improving cropping systems (Ruiz-Ramos and Minguez, 2010).

On these premises, this simulations carried out for this research aimed to assess the impact of climate change on yield, water use and *WF* (green and blue) of wheat cultivated in two European sites, located in Germany and Italy; and rank the multiple sources of prediction uncertainty. For this purpose, four crop simulation models, two main European wheat producing areas, seven soils (four for Italy and three for Germany), two CO_2 concentration pathways (*RCP_4.5 and RCP_8.5*; IPCC, 2014), five climate scenarios from General Circulation Models (*GCM*) compared to the baseline and two reference evapotranspiration models (Priestley-Taylor; Priestley and Taylor, 1972 and Penman–Monteith; Allen et al., 1998) were implemented in this simulation study.

2. Materials and methods

2.1. Characterization of the study areas

Italy and Germany are two major countries for winter wheat cultivation. More than 14% of grain yield in the EU (34,926,626 of tonnes in 2014) was produced in these two countries (FAOSTAT, 2017). Orsara di Puglia (*Ors*) and San Paolo di Civitate (*San*) located in Foggia district (Southern Italy) were selected as representative areas for durum wheat (*Triticum turgidum* L., subs. *durum* [Desf.]) cultivation in Italy, whereas Manschnow (*Mann*) and Müncheberg (*Mub*) belonging to Märkisch-Oderland district (East Germany) were selected for soft wheat (*Triticum aestivum*, L.) cultivation in Germany (Fig. 1). In 2011, Foggia district covered more than 13% of the overall durum wheat production in Italy, that means 3,858,481 of tonnes (ISTAT, 2017), while Märkisch-Oderland district represents an area, which is marginal for wheat production due to poor soils and low annual precipitation. This is expressed in relatively low wheat yields of 5.7 t ha^{-1} (1999–2011, Statistische Ämter des Bundes und der Länder, 2018) and a low share in German wheat production of, e.g., 0.8% in 2010 (Amt für Statistik Berlin-Brandenburg, 2011; Federal Statistical Office Germany, 2011). The climate of Foggia district is "accentuated thermo-Mediterranean" (FAO-UNESCO classification, 1963), with minimum temperatures below 0 °C in the winter and maximum temperatures above 40 °C in the summer. Annual rainfall (mean 550 mm over a 50-year period 1965–2015) is mostly concentrated during the winter months and the "Class A evaporation pan" evaporation exceeds 10 mm d^{-1} in summer (average of maximum daily values recorded in July and August). The climate of Märkisch-Oderland district is "Continental", having an annual mean temperature of 9.3 and 9.4 °C (averages for 1992–2012 period) for *Mub* and *Mann*, respectively. The coldest monthly Average annual potential grass evapotranspiration (for 1991–2010 period) is at 596 and 640 mm for *Mub* and *Mann*, respectively (DWD, 2018). Coldest month mean temperature is at 0 °C and five months are above 10 °C. The annual precipitation during the time of investigation varies

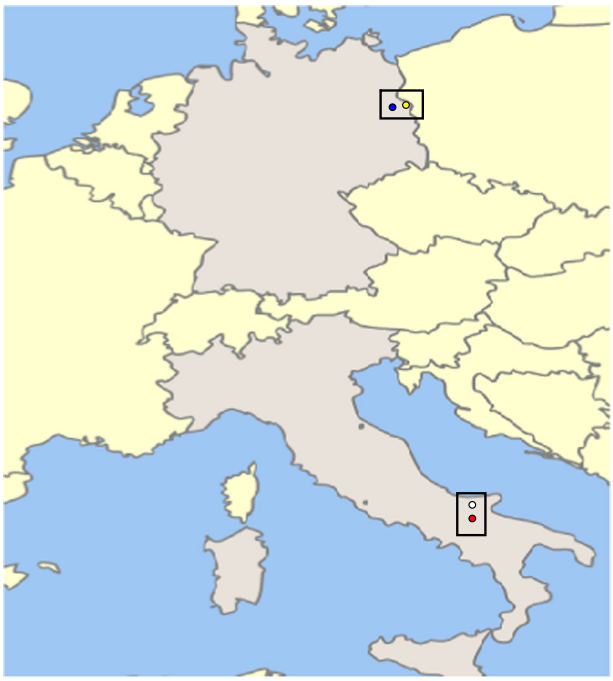

Fig. 1. Location of the two analysed areas in Italy (white circle; San Paolo di Civitate, red circle; Orsara di Puglia) and Germany (yellow circle; Manschnow; blue circle Müncheberg).

between 363 and 793 mm and 344–749 mm for *Mub* and *Mann*, respectively.

Typical soils were considered to represent the characteristics of the areas under study, showing a high heterogeneity as described in Tables 3 and 4. For the Italian sites, homogeneous pedologic areas were based on a detailed clustering procedure and subsequent interpolation of soil data using geostatistical techniques (Castrignanò et al., 2010). This area classification was adopted by Ventrella et al. (2012a) to select the most relevant soil. Three main soil types for Märkisch-Oderland were extracted from the 1:1.000.000 soil map of Germany using their representative profile description (Hartwich et al., 1995). The crop-soil management set up for each simulation model was based on the common wheat practices performed in the locations under study. Inin Märkisch-Oderland district the management consists of a stubble tillage (0.30 cm depth) three days after the grain harvesting, application of nitrogen (N) fertilization as top dressing with 180 kg N ha^{-1} split in three doses (60 kg N ha^{-1}, 70 kg N ha^{-1} and 50 kg ha^{-1} form from the second half of March to the end of May). Sowing takes place at the beginning of October and the harvest is performed in late July. In Foggia district, the common tillage practice is ploughing in late summer, followed by disk harrowing a few weeks before sowing followed by seed-bed preparation with a field rototiller, as formalized in each model. Nitrogen fertilization is performed before sowing with 60 kg N ha^{-1} of urea and with 60 kg N ha^{-1} of ammonium nitrate as topdressing. Sowing occurs at the beginning of November, and harvest during the first decade of June.

2.2. Baseline and future wheatear projections

For the baseline scenario (*Bas*), a synthetic time series of 100 years was generated from 30 years (1982–2012) of observed daily data, including maximum and minimum temperature (°C); rainfall (mm); relative humidity (%); wind (m/s); global solar radiation (MJ m^{-2} d^{-1}) using the MaRfi generator (Dubrovsky et al., 2004). To assess the trend of weather until 2050, five Global Circulation Models (*GCM*) and two contrasting representative CO_2 Concentration pathways (*RCP_4.5* and *RCP_8.5*) were used to perturb the weather generator parameters. Then 100-years synthetic weather series were generated, representing the change considered by the combination of each *RCP* and *GCM* for evaluating the effect of different climate projections (IPCC, 2014) on crop production and water consumption. *GCMs* taken into account for this investigation were: i) Beijing Normal University Earth System Model (*BNU*; Ji et al., 2014); ii) Centre National de Recherches Météorologiques—Groupe d'études de l'Atmosphère Météorologique, CNRM-CM5.1 global climate model (*CNRM*; Voldoire et al., 2013); iii) Hadley Centre Global Environmental Model version 2 (*HAD*; The HadGEM2 Development Team et al., 2011); iv) Institut Pierre Simon Laplace-5th Phase of the Coupled Model Intercomparison Project (*IPSL*; Dufresne et al., 2013); v) global coupled atmosphere-ocean general circulation model (*MRI*; Yukimoto et al., 2006). Atmospheric CO_2 concentration for *Bas* was set at 360 ppm, whereas the two extremes of *RCP* were set at 486 ppm (*RCP_4.5*) and 540 ppm (*RCP_8.5*; IPCC, 2014).

2.3. Simulation experiment design

2.3.1. Crop simulation models

For assessing grain yield, water consumption and *WF* of winter wheat under different climate scenarios, four crop simulation models were applied: Cropsyst (v. 4.15.17), Aquacrop (v.6), Hermes (v.4.26) and DSSAT (v. 4.5).

2.3.1.1. CropSyst. CropSyst (*CPS*, Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time-step crop growth simulation model, designed to serve as an analytical tool to study the effect of cropping system management on crop productivity and on the environment (Stöckle et al., 2003). Water dynamic is simulated by cascade or finite difference approaches.

The daily potential above-ground biomass (*AGBpt*) is calculated as the minimum value between the values estimated by transpiration use efficiency (Tanner and Sinclair, 1983) and that by radiation use efficiency (Monteith, 1977). Water and nitrogen limiting factors are then applied to *AGBpt* to calculate actual AGB production (*AGBa*). The biomass production affected by a water-limited condition (*AGBt*) is calculated taking into the effective water uptake by the crop. For the calculation of crop water uptake, the soil profile is divided into layers and the water uptake of each layer is calculated from the water potential difference between the soil and the plant xylem, multiplied by plant conductance (mainly determined by root conductance). Soil water potential, leaf water potential just before the beginning of stomatal closure due to water deficit, wilting plant leaf water potential, are parameters involved in the calculation of *AGBt*.

Daily *AGBa* production is calculated by multiplying *AGBt* by a coefficient based on plant nitrogen concentration (Stöckle and Debaeke, 1997). Final yield is computing multiplying the *AGBa* by the harvest index, the latter modified as consequence of temperature and nitrogen stress during flowering and grain filling phases.

2.3.1.2. Aquacrop. The AquaCrop (*AQC*) model was developed by the FAO in 2009, with a detailed description presented by Steduto et al. (2009) and Raes et al. (2009). The model computes a daily water balance, and separates evapotranspiration into evaporation and transpiration components. Transpiration is estimated as a function of the canopy cover, expressed as percentage of soil cover, and evaporation is proportional to the area of soil not covered by vegetation. Potential transpiration is calculated by multiplying the fraction of canopy cover by the crop coefficient (*Kc*) and reference evapotranspiration (*ETo*). From the potential transpiration (*Tp*), Aquacrop computes the actual transpiration (*Ta*) by accounting for the effect of water stress (by means of stress coefficients) which affects the canopy development (reduction), stomatal closure

(increase), canopy senescence (quickening), and the harvest index (increase or decrease); all proportionally to the degree of water stress. Biomass is calculated by multiplying *Ta* by the water productivity normalized (*WP*) by *ETo*, to take into account the interaction between the crop and environment given the normalized crop water productivity (*NCWP*) which is considered constant for a given climate condition and crop (even if *NCWP* can decrease during the reproductive phase). Aquacrop does not simulate nitrogen dynamics, so any stress on plants in nutrient-limited conditions are modulated throughout categories of stress (from slight to severe deficiency) provided by the model, which affect *NCWP*.

2.3.1.3. Hermes. The model (*HRM*, Kersebaum, 1995; Kersebaum and Beblik, 2001) simulates net mineralization as a function of temperature and soil moisture content from two pools of potentially decomposable nitrogen (Richter et al., 1982) which are derived from soil organic matter and amount of crop residue related to the yield of the previous crop. The sub-model for crop growth was built on the basis of the SUCROS model (van Keulen et al., 1982). Daily net dry matter production by photosynthesis and respiration is driven by radiation and temperature. Gross CO_2 assimilation is calculated from global radiation and temperature using a radiation interception approach described by Penning de Vries and van Laar (1982). Maintenance respiration is depending on air temperature and calculated as sum of organ specific dry matter weight, while growth respiration is calculated as a fixed partition of daily assimilated carbon. Assimilates are assigned to the crop organs according to a partitioning matrix, which is organised by the crop's developmental stages. The crops development in turn is calculated from the sum of degree days modified by stage specific requirements for day length and vernalisation. Potential crop cover specific evapotranspiration (*ETp*) is calculated multiplying *ETo* by a development stage related *Kc* factor and partitioned to transpiration *Tp* and evaporation *Ep* depending on simulated *LAI*; *Ep* is adjusted depending on top soil water content and distributed over depth using a texture dependent exponential function; *Tp* is converted to actual transpiration *Ta* depending on root distribution and soil water availability. The model considers daily capillary rise from shallow groundwater depending on soil texture and actual distance between water depletion zone and groundwater surface. Finally, if the ratio between actual and potential transpiration is below a development stage specified threshold, the amount daily net-assimilation is reduced by a logistic stress function. Grain yield is calculated from the biomass partitioned to ears at harvest.

2.3.1.4. DSSAT. The model (*DST*, Jones et al., 2003) computes daily plant growth by converting daily intercepted photosynthetically active radiation into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception is computed as a function of LAI, plant population, and row spacing. Leaf area expansion is modified by daily temperature GDD, and water and nitrogen stress. The daily canopy photosynthesis predicts daily gross photosynthesis as a function of daily irradiance for a full canopy, which is then multiplied by factors for light interception, temperature, leaf nitrogen status, and water deficit. The amount of new dry matter available for growth each day may also be modified by the most limiting of water or nitrogen stress, and temperature, and is sensitive to atmospheric CO_2 concentration. Above ground biomass has priority for carbohydrate, and at the end of each day, carbohydrate not used for above ground biomass is allocated to roots. Starting from *ETo*, the model calculates the potential plant transpiration and actual transpiration, the latter affected by weather and soil limitations. Potential root water uptake is computed by calculating a maximum water flow to roots in each layer and summing these values (Jones and Ritchie, 1991). These calculations account for root length density in each layer and the soil water content in the layer. The actual plant transpiration is then computed as the minimum of potential plant transpiration and the potential root water uptake. Thus, the atmosphere can limit transpiration by low solar radiation and cool temperatures, the canopy can limit it by low LAI, and the soil can limit it by low soil water content and low root length density. The ratio of actual ET to potential ET reduces photosynthesis in proportion to relative decreases in transpiration.

2.4. Simulations in current and future climate scenarios

After calibration and validation steps, two fundamental phases required to align the output of the models to the data cropped up in experimental trials (for details see Garofalo et al., 2009; Kersebaum et al., 2016; Gobin et al., 2017), the weather-input files were set to simulate the baseline and future scenario projections. Sowing date and harvest time were November, 5th and June 20th, respectively, for the Italian sites and October, 3rd and 2nd August, respectively, for the German sites. Soil tillage and N fertilizations followed the criteria earlier explained, whereas straw was simulated to be left on the soil after harvest and buried during the following soil tillage practices.

According to Siebert and Döll (2010), the consumptive use of *GW* and *BW* was estimated from the soil/plant water balance as simulated by the models in two steps: *GW*, by assessing the water consumption of wheat under rainfed management and *BW* when the crop was supplied with irrigation water.

Such approach was adopted also by Ventrella et al. (2015, 2017) for winter durum wheat and tomato in a regional assessment for crop cultivation in the Apulia region (Southern Italy).

Rainfed and irrigated management were simulated in order to obtain the grain yield, blue water (*BW*), green water (*GW*) and the water footprint (*WF*), as follows:

$$GW = ETc_{no\_irr} \tag{1}$$

$$BW = ETc_{irr} - GW \tag{2}$$

where ETc_{no_irr} and ETc_{irr} are the actual crop evapotranspiration under rainfed and irrigated management, respectively. Irrigation was triggered whenever the water depletion of available water content reached 50% in Germany and 80% in Italy and the period for the water supply was set from April, 15th to July, 15th for German sites and from March, 15th to May, 10th for the Italian sites.

WF under rainfed and irrigated treatments was expressed in terms of t of grain yield (14% of moisture) on m^{-3} of water used as:

$$WFrain = WF\_GW = \frac{GW}{Yield\_RF} \tag{3}$$

$$WFirr = WF\_GW + WF\_BW = WF\_T = \frac{GW + BW}{Yield\_IR} \tag{4}$$

where *Yield_RF* and *Yield_IR* are the grain yield under rainfed and irrigated conditions, respectively.

Baseline (*BAS*) and future climate scenarios (*GCM* and *RCP*) were used in combination with all the crop simulation models. *CPS* and *DST* shared the same sites, soils and ET_0 model (Priestley-Taylor, *PT*). One location and one soil for Italy, two locations with all soils for Germany and the Penman–Monteith ET_0 model (*PM*) were used to perform simulations with *AQC*. For *HRM*, all combinations of sites, soils and ET_0 models were applied for all simulation experiments (Table 5).

2.5. Statistical analysis

Komologorov-Smirnov-Lilliefors (*KSL*) and Levene tests were used to assess the normal distribution and homogeneity of variance, respectively. Once corroborating the lack of both the assumptions, in order to assess significant differences within the different "factors" (model, location, soil, *GCM*, *RCP*, *ETp* equation) the non-parametric, rank-based Kruskal-Wallis (*KW*) test was performed. With this test, the contribution of each factor in impacting the analysed parameters was assessed

by calculating the mean of the ranks for each factor and then determining the absolute value of the difference between the mean of the rank of each factor and the total average. Statistical analysis was carried out using JMP software version 10.0 (SAS Institute Inc., 2010).

3. Results

3.1. Weather trends

Rainfall, maximum temperature (*Tmax*) and minimum temperature (*Tmin*) of *BAS* are reported in Tables 1 and 2 and differences of weather variables between *Bas* and *GCMs* for both European locations during the wheat growing period are shown in Figs. 2, 3, 4 and 5.

For German sites, all *GCMs* except for *BNU*, showed an increase in total rainfall during the growing cycle both for *RCP_4.5* and *RCP_8.5* that ranged from a minimum of 0.4 mm y^{-1} (*Mann*, *IPSL*, *RCP_4.5*, Fig. 2) to a maximum of 6.1 mm y^{-1} (*Mub*, *CNRM*, *RCP_8.5*, Fig. 3). Despite the agreement in forecasting the annual increment in rainfall among *GCMs*, their paths were quite diverse. For instance, *CNRM* indicated higher rainfall compared to baseline along the growing periods (both for *RCP_4.5* and *RCP_8.5* and for both sites) whereas *HAD* was slightly drier only in July and *MRI* in May. Finally, the last three months of the growing season were constantly drier under *IPSL* with respect to *BAS*, and a lower rainfall in *RCP_8.5* rather than in *RCP_4.5*. *Tmax* was expected to increase in all *GCMs* and *RCPs* compared to *BAS*, from a minimum of 1.5 °C (averaged for all *GCMs*, *RCP_4.5* and both sites) to 1.9 °C shifting from *RCP_4.5* to *RCP_8.5*. Increments of *Tmax* were predicted for all months, but the winter period and the last part of growing period showed the largest gap between *BAS* and the remaining *GCMs*; this gap was more accentuated in *RCP_8.5* than *RCP_4.5*.

Changes in *Tmin* were in line with those predicted for *Tmax*, with a gap compared to *BAS* equal to +1.50 °C in *Mann* and +1.44 °C in *Mub* (average value for all *GCMs* and *RCP_4.5*). However, the effect of *RCP_8.5* on *Tmin* resulted in a more pronounced variation compared to *RCP_4.5*, showing a further increment equal to +0.49 °C in addition to *RCP_4.5*.

Concerning Italian sites, *GCMs* agreed on a small reduction of rainfall in *Ors* both for *RCP_4.5* (−1.4 mm y^{-1} on average) and *RCP_8.5* (−1.8 mm y^{-1} on average) during the crop growing period compared with *BAS*; however, this trend was less pronounced in *San*.

Table 1
Main weather variables for baseline (*Bas*) of German sites.

Site	Month	Maximum temperature	Minimum temperature	Rain
		Mean (°C)	Mean (°C)	Sum (mm)
Manschnow	Nov	6.8	1.4	30.8
	Dec	2.2	−1.6	30.9
	Gen	1.7	−2.6	30.0
	Feb	2.8	−2.8	28.0
	Mar	8.3	0.4	28.0
	Apr	14.7	3.5	28.2
	May	19.9	7.7	48.4
	Jun	22.6	10.8	48.7
	Jul	25.1	13.1	60.8
Müncheberg	Nov	6.1	1.1	37.4
	Dec	1.6	−1.7	41.6
	Gen	1.0	−2.6	38.0
	Feb	3.1	−2.2	31.9
	Mar	8.1	0.3	36.4
	Apr	14.6	3.3	32.6
	May	20.0	7.8	55.5
	Jun	22.1	10.6	58.9
	Jul	24.6	13.1	63.5

Table 2
Main weather variables for baseline (*Bas*) of Italian sites.

Site	Month	Maximum temperature	Minimum temperature	Rain
		Mean (°C)	Mean (°C)	Sum (mm)
Orsara di Puglia	Nov	14.5	6.8	54.5
	Dec	11.4	4.3	42.7
	Gen	9.9	2.8	42.5
	Feb	11.2	2.7	32.9
	Mar	13.0	4.6	35.5
	Apr	17.1	7.4	34.5
	May	21.9	11.3	37.1
	Jun	27.3	15.7	32.9
	Jul	29.6	18.2	24.3
San Paolo di Civitate	Nov	17.0	8.0	59.7
	Dec	13.3	5.3	67.3
	Gen	11.9	3.1	42.5
	Feb	13.5	3.7	36.3
	Mar	15.6	4.5	32.9
	Apr	19.2	7.5	35.7
	May	24.2	11.7	34.7
	Jun	28.8	15.4	22.6
	Jul	32.0	18.7	26.5

GCMs pointed out an equal increment in terms of *Tmax* and *Tmin* under both sites and *RCPs*. Namely, the gap in terms of *Tmax* during the growing crop cycle was +1.4 °C (*RCP_4.5*) and +1.9 °C (*RCP_8.5*) with respect to *BAS* for both *Ors* and *San*; *GCMs* predicted an increment of *Tmin* equal to 1.4 °C (*RCP_4.5*) and +1.8 °C (*RCP_8.5*) in comparison to *BAS*.

Overall, the temperature increment was equally distributed, with absence of peaks during the crop growing months.

3.2. Yield, water use and water footprint in future projections

Table 6 and Figs. 6 and 7 summarize the effect of *RCPs* on yield, water consumption and related *WF* with respect to *BAS*.

3.2.1. Germany

Under rainfed management, winter wheat production was higher in *RCP_4.5* and *RCP_8.5* as compared to *BAS* (6.5 t ha^{-1} as mean vs. 5.9 t ha^{-1}). Irrigation positively affected the grain yield, leading to an increment of 1.4 t ha^{-1} with respect to rainfed productivity both for *BAS* and all *GCMs* (Table 6).

The cumulated probability function confirmed the benefit of *RCPs* on wheat performance. For instance, considering the average yield under rainfed condition and a hypothetical threshold reduction of −25% (4.5 t ha^{-1}, 4.97 t ha^{-1} and 5.03 t ha^{-1} for *BAS*, *RCP_4.5* and *RCP_8.5*, respectively), the cumulated probability to obtain lower wheat productivity was equal to 41% in *BAS* and 33% in *RCPs* (Fig. 6). Similarly, grain yield under rainfed management at a cumulated probability of 75%, was 8.3 t ha^{-1} in *RCPs* (+40% compared with the mean value), whereas 6.94 t ha^{-1} (+17% with respect to the mean value) was the grain yield found out in *BAS*.

However, an increased yield did not correspond to a higher water consumption by the crop, neither in terms of green water nor in terms of blue water.

Green and blue water in *BAS* and *RCP* scenarios, kept stable values around 370 mm for *GW* and 51 mm for *BW* indicating that that most of water consumption was as *GW* (88%) rather than *BW* (12%). In addition, the related probability functions did not underline different paths among *RCP* scenarios. Consequently, the water footprint of green water (*WF_GW*) and water footprint of total water footprint (*WF_TW*) resulted in lower values under future weather trends as compared to *BAS*.

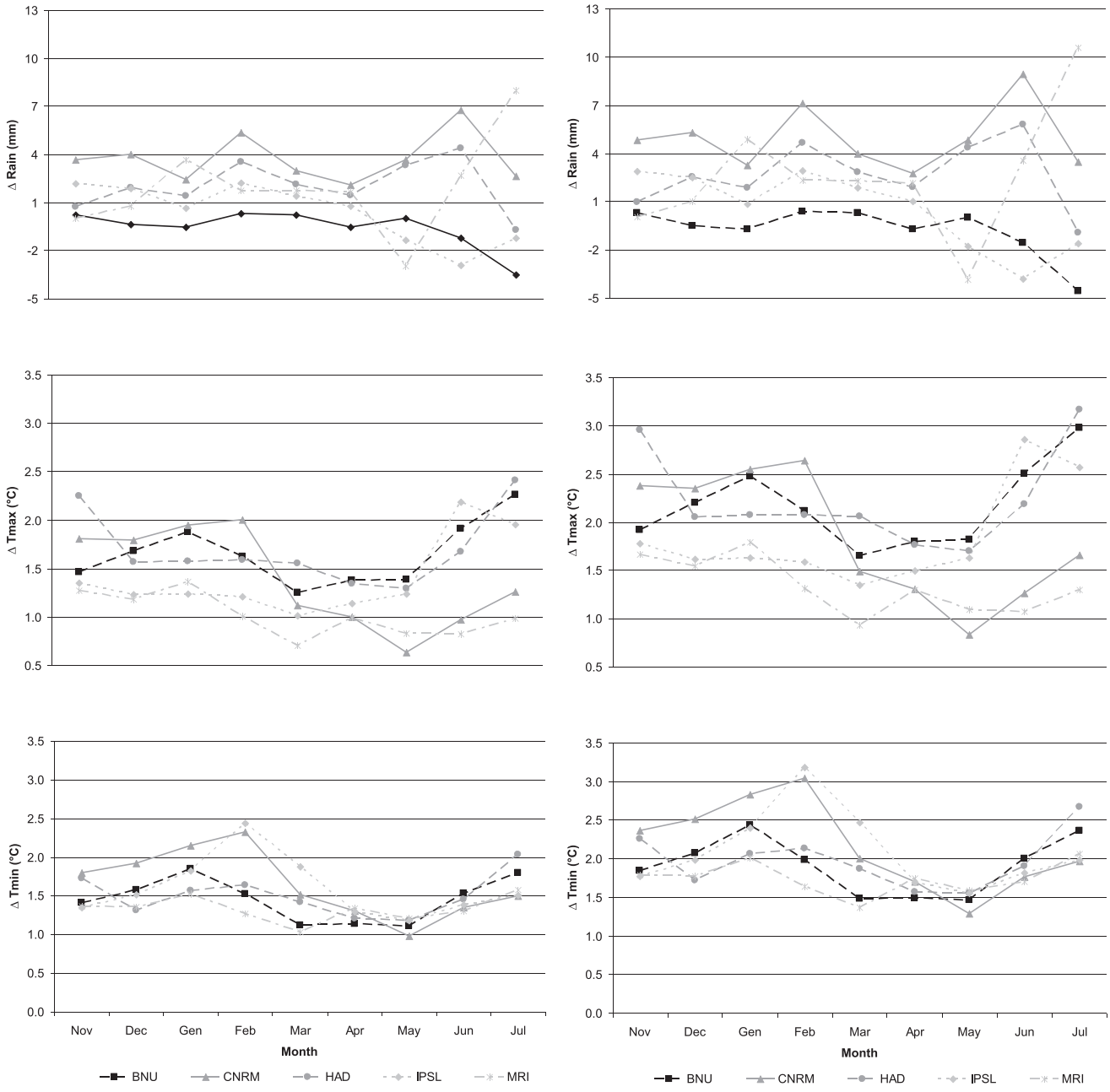

Fig. 2. Differences of the main weather parameters between baseline (*Bas*) and global circulation models (GCMs) for Mann (Manschnow, Germany) site as predicted by *RCP_4.5* (left) and *RCP_8.5* (right) during the growing period.

In each scenario, irrigation contributed to lowering *WF*, i.e. the water consumption per ton of grain yield, by −9% in *BAS* (849 m^{-3} t^{-1} vs 930 m^{-3} t^{-1}) and −12% in *RCP*s, indicating as irrigation had positive effect on several bio-mechanisms underlying the crop performance. The high steepness of the curve (more pronounced in *RCP*s than in *BAS*) pointed out that *WF* was a fairly stable indicator in the range of cumulated probability values from 25 to 75% and it was a good indicator of grain yield as a function of water consumption.

3.2.2. Italy

Forecasted climate scenarios, did not lead to substantial changes in durum wheat yield, the latter with an average value stable at 4.0 t ha^{-1} for *BAS* and *RCP*s (Table 6). In addition, the cumulative cumulated probability function confirmed the unchanged crop productivity, even when searching for variation of grain yield at different percentages along the curve of cumulative frequency distribution (Fig. 7).

Irrigation boosted the crop productivity for all *RCP*s, equally, improving the yield of about 18% and the course of cumulative distribution function remained unchanged between CO_2 scenarios.

Water demand was satisfied for the most part by the green water (83% as mean), with a value slightly higher in *BAS* compared to the other CO_2 pathways; this led to a higher *WF_GW* calculated for *BAS* with respect to *RCP_4.5* and *RCP_8.5*. Irrigation improved wheat productivity per unit of water consumed by crop, resulting in a lower *WF_TW* compared to *WF_GW*. These two parameters were confirmed as stable indicators of crop productivity as a function of water used under a wide range of pedo-climatic conditions.

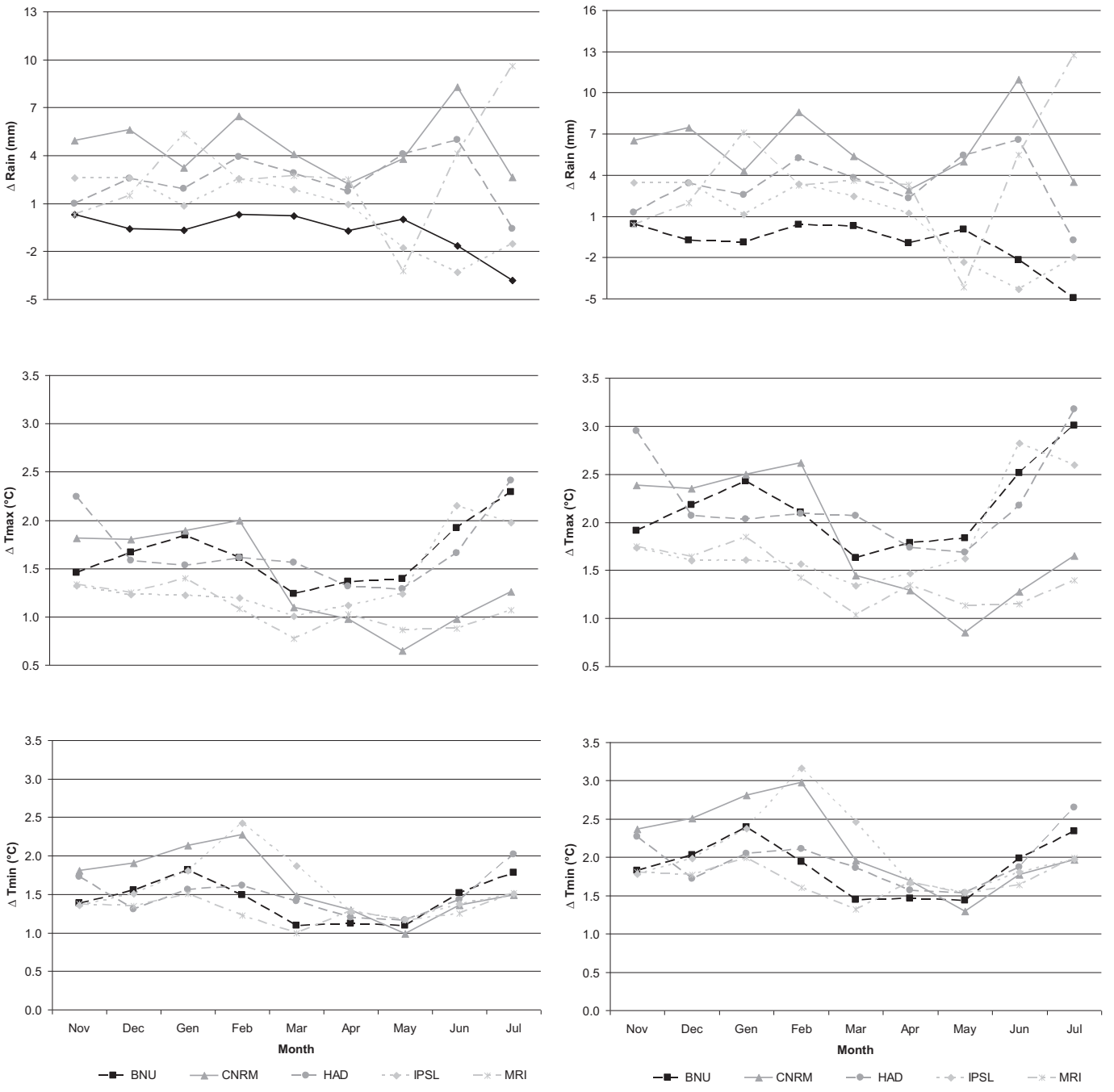

Fig. 3. Differences of the main weather parameters between baseline (*Bas*) and global circulation models (GCMs) for *Mub* (Müncheberg, Germany) site as predicted by *RCP_4.5* (left) and *RCP_8.5* (right) during the growing period.

3.3. Uncertainty of predictions under climate changes projections

The effect of each factor is explained in box-plots showing the 25, 50, and 75th quartile and the interquartile range (*IQR*; Figs. 8–14).

3.3.1. Uncertainty in Germany

Concerning crop yield, the median of the modelling ensemble was equal to 5.9 t ha^{-1} under rainfed scenarios, but with a wide difference among crop models, with the lowest median (4.6 t ha^{-1}) for *HRM_PM* and the highest (11.1 t ha^{-1}) for *CPS*. The difference in terms of median score resulted less pronounced when comparing yield under irrigated scenarios, since as only *CPS* kept the same crop performance, whereas the median shifted toward higher values for the remaining crop models. However, in both rainfed and irrigated management, *IQR* resulted higher in *HRM* model compared to the other crop models (Fig. 8).

The lowest median of water used by the crop (both the *GW* and *BW*) was for *CPS*, whereas the other models provided aligned responses. As a consequence, differences among models in terms of *WF_GW* and *WF_TW* (median) were evident, with *CPS* that simulated 260 m^3 t^{-1} for both *WF_GW* and *WF_TW*, far lower if compared to the median of ensemble modelling (688 m^3 t^{-1} and 557 m^3 t^{-1} for *WF_GW* and *WF_TW*, respectively).

Median scores of the grain yield observed for *GCMs* were consistently higher with respect to *BAS* under both rainfed and irrigated

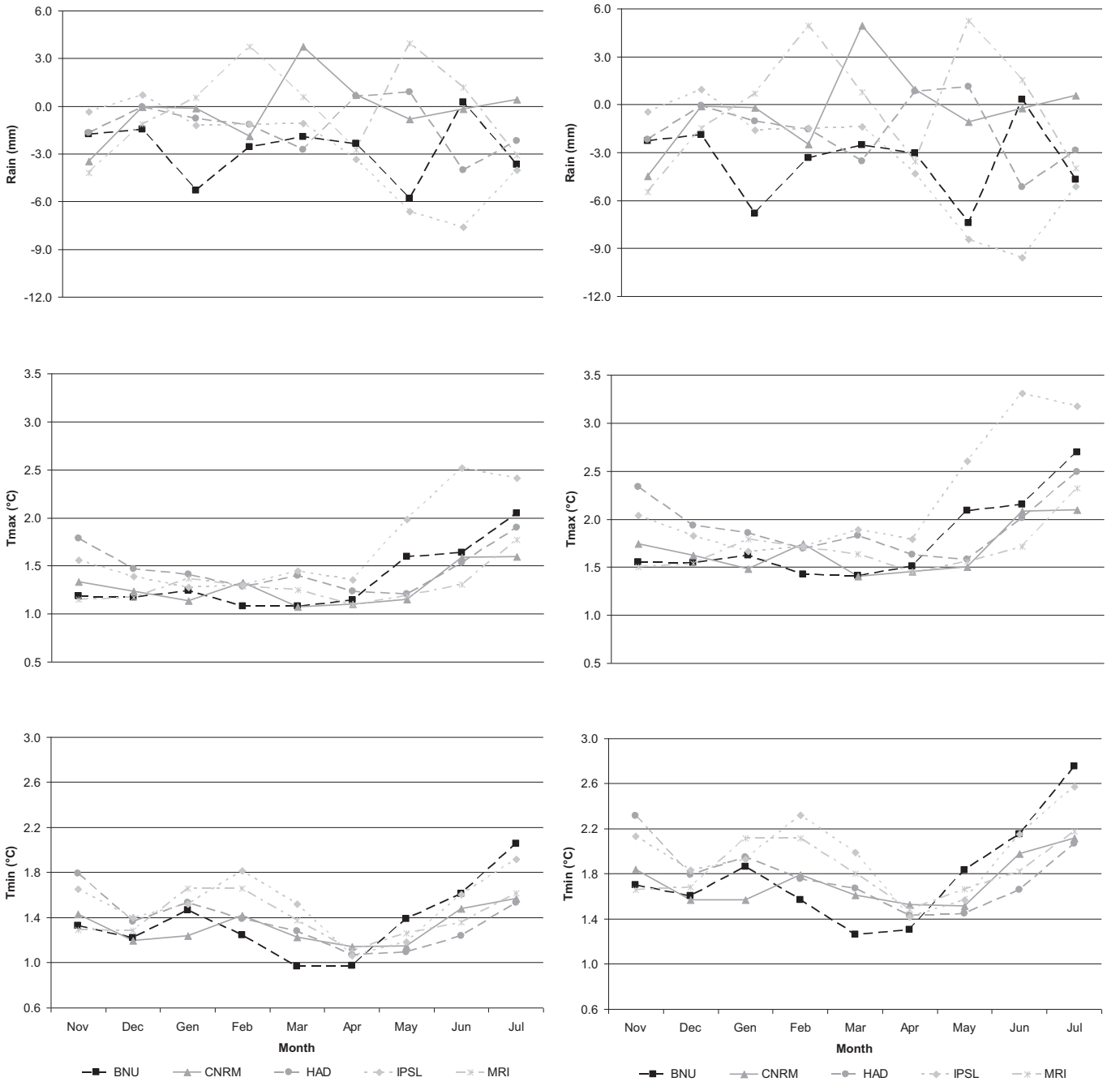

Fig. 4. Differences of the main weather parameters between baseline (*Bas*) and global circulation models (GCMs) for *Ors* (Orsara di Puglia, Italy) site as predicted by *RCP_4.5* (left) and *RCP_8.5* (right) during the growing period.

schemes. Interestingly, with irrigation, *IQR* for *GW* and *BW* oscillated in a limited range (369–402 mm for the former and 32–45 mm for the latter), resulting in a higher *WF* (median) and its variability under *BAS* compared to the other *GCMs* (Fig. 10). Higher yield was simulated for *Mub* site if compared to *Mann* site, under both rainfed and irrigated management. Irrigation reduced the yield variability in *Mub* site (from 3.4 to 3.0 t ha^{-1}), whereas the production was not affected by the water supply in *Mann* site. In addition, the median values for *GW* and *BW* were comparable between sites; as a results, the score for *WF_GW* and *WF_TW* in *Mann* area was higher (and with a higher variability) of 22% and 8% respectively, with respect to *Mub* location (Fig. 12).

A wide range of median values was observed for the yield cropped up on different soils, with the highest score observed in Fluvisol (*Flu*; 4.99 t ha^{-1}) followed by Podzol (*Pod*; 5.5 t ha^{-1}) and finally Cambisol (*Cam*; 6.84 t ha^{-1}). If irrigated, grain yield of *Flu*, *Cam* and *Pod* soils improved, with the latter two showing comparable performance. A large yield variability (expressed by *IQR*) was observed under rainfed (4.47 t ha^{-1}) and irrigated management (4.31 t ha^{-1}) in *Flu* soil; for the other soils, deviation from the median value was more confined, further reduced with water supply (Fig. 12).

Moreover, *Cam* soil showed the highest median value for water consumption under rainfed regime coupled with the lowest *BW* and for both the factors, the smallest variability. The overall image for the

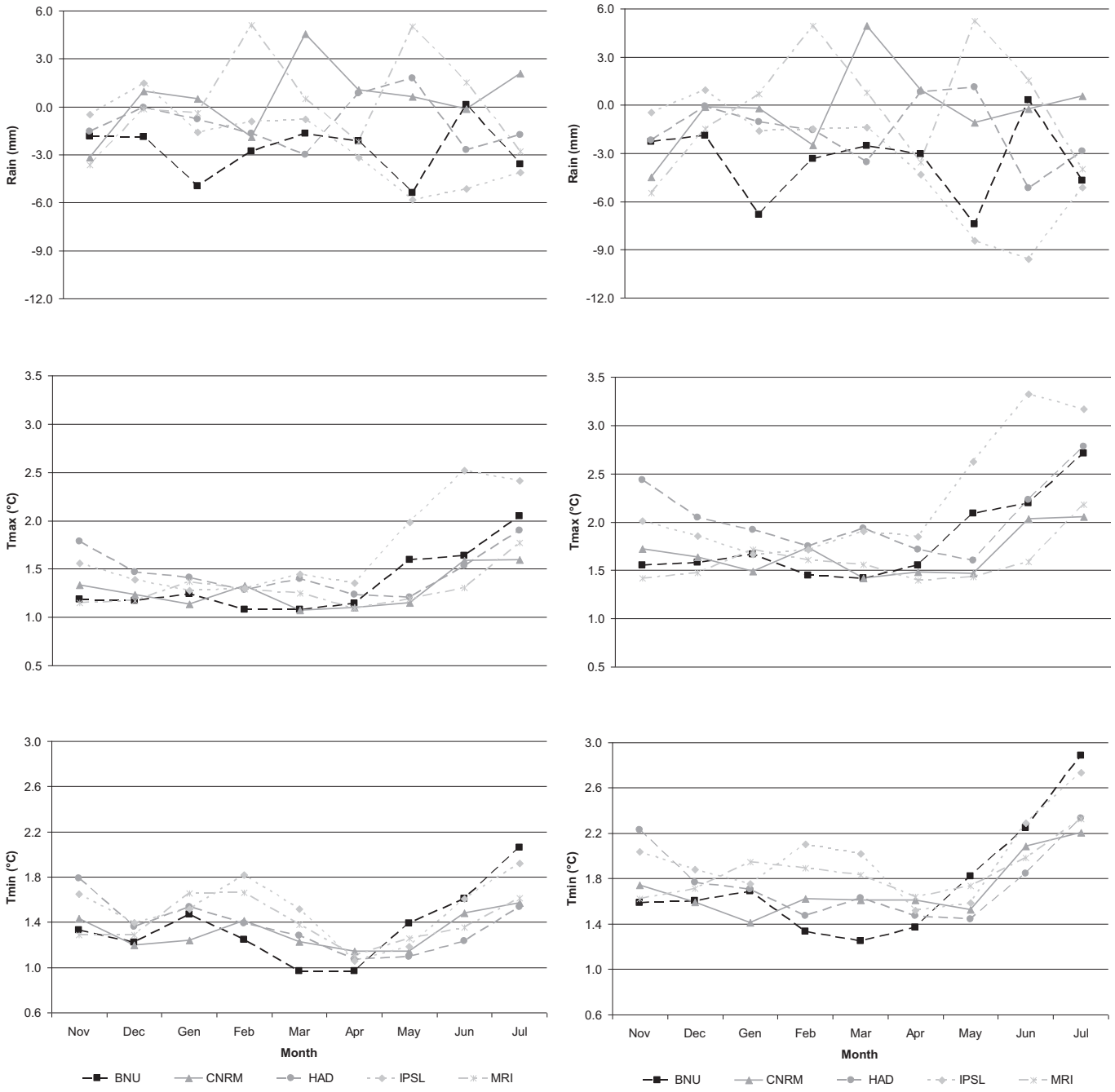

Fig. 5. Differences of the main weather parameters between baseline (*Bas*) and global circulation models (GCMs) for *San* (San Paolo di Civitate, Italy) site as predicted by *RCP_4.5* (left) and *RCP_8.5* (right) during the growing period.

median is that *Cam* soil had the lowest *WF_GW* value (616 $m^3\ t^{-1}$), followed by *Pad* soil (678 $m^3\ t^{-1}$) and *Flu* soil (825 $m^3\ t^{-1}$), whereas comparable median *WG_TW* values were obtained in *Cam* and *Pad* soils (513 $m^3\ t^{-1}$), the highest observed in *Flu* soil (795 $m^3\ t^{-1}$).

The median of simulated yield (both under rainfed and irrigated schemes) in response to enriched atmospheric CO_2 concentrations was above the median observed for *BAS* scenario; the positive effect of irrigation, other than the improvement of crop productivity, was the reduction in terms of variability of its distribution.

Increment of atmospheric CO_2 concentration did not result in a higher median score of water consumed by crop (blue and green); as a consequence, the median value calculated for *WF_GW* and *WF_TW* under *RCP_4.5* and *RCP_8.5*, resulted in lower water consumption and related variability in comparison to *BAS* (Fig. 14).

Under rainfed conditions, differences in terms of median score for grain yield were observed between *PM* and *PT* evapotranspiration models; the highest median score, 25th quartile, 75th quartile and *IQR* were observed in *PT* model. Anyway, under irrigated management the median value was aligned between evapotranspiration models, even if *IQR* calculated for *PT* model was higher compared to *PM* model. The median score of *GW* observed in *PM* model was slightly higher than *PT* model, but the score of *BW* resulted more than doubled in *PM* than *PT*. However, *PT* model showed the largest variability (see *IQR*) both for *GW* and *BW*.

Table 3
Main soil characteristics used in simulations for German area.

Location	Soil	Depth	Sand	Silt	Clay	WP	FC	Bulk density
		cm	%	%	%	vol%	vol%	g cm^{-3}
Manschnow	Flu	30	18.0	65.0	17.0	12	39	1.35
		70	18.0	65.0	17.0	12	37	1.45
		130	18.0	65.0	17.0	12	37	1.50
		200	70.0	5.0	25.0	6	23	1.60
Muncheberg	Cam	30	71.0	20.0	9.0	9	31	1.30
		40	70.0	25.0	5.0	6	24	1.35
		80	53.0	25.0	22.0	15	28	1.65
		200	58.0	26.0	16.0	12	29	1.60
Muncheberg	Pod	30	88.0	8.0	4.0	5	14	1.30
		50	88.0	8.0	4.0	3	11	1.60
		200	88.0	8.0	4.0	5	14	1.50

Table 4
Main soil characteristics used in simulations for Italian area.

Location	Soil	Depth	Sand	Silt	Clay	WP	FC	Bulk density
		cm	%	%	%	vol%	vol%	g cm^{-3}
Orsara; San Paolo	1	40	28.9	32.6	38.5	34.2	19.4	1.29
		80	22.0	33.8	44.1	43.7	26.8	1.26
San Paolo	5	40	36.84	29.4	33.7	31.2	17.4	1.32
		80	23.43	30.5	45.9	43.3	27.5	1.25
Orsara; San Paolo	6	40	36.53	39.55	23.9	34.2	19.1	1.15
		80	24.85	36.3	39.0	42.5	24.5	1.13
Orsara	8	40	37.6	31.3	31.0	31.1	17.1	1.34
		80	31.1	35.7	33.2	38.4	20.6	1.32

Thus, the median of *WF_GW* and *WF_TW* shifted toward higher values for *PM* model than for *PT*, keeping at same time the lowest *IQR* (Fig. 14).

3.3.2. Uncertainty in Italy

The highest median value of yield was observed for *DST*, the lowest for *HRM_PM*. *AQC* showed a very narrow yield variability, whereas *DST* and *HRM_PT* had the highest one. Generally, irrigation had a positive effect on the median score of grain yield, raising the value from 4.2 t ha^{-1} to 5.1 t ha^{-1} and reducing the variability of performance in all crop models. *AQC* and *DST* indicated a higher consumption of green water with respect to the other crop models, with the remaining models that showed comparable median values for this parameter. Manifold responses were simulated for the median of blue water, since the values ranged from a minimum close to 0 mm in *CPS* to a maximum of 91 mm in *HRM_PM*, which in turn showed also a high asymmetry in simulated data. Moreover, *CPS* provided a very low *IQR*, followed by *AQC* and finally *DST* and *HRM*, the latter with both *PM* and *PT* evapotranspiration models (Fig. 9).

Concerning *WF_GW* and *WF_TW*, three models out of five were aligned in their response (median scores between 518 and 540 m^3 t^{-1} for *CPS* and *DST*, and slightly above 550 m^3 t^{-1} for *HRM_PT*), far less than the values indicated by *AQC* and even more than *HRM_PT*, which showed also a very high variability (Fig. 9).

Median and variability of all analysed parameters under *CGMs* scenarios provided comparable patterns; the highest variability was associated to *BW* as consequence of the highest erraticism in weather trends over the simulated years. The high asymmetry of *WF_GW* under all *GCMs* scenarios should be noted, with the median value moved downwards indicating the presence of some years very droughty that led to a lower productivity coupled with higher "unproductive" water consumption. This condition was softened by irrigation, which determined a lower variability and a more regular distribution of *WF_BW* data (Fig. 11). Location did not affect yield and water consumption and related water footprint, since as median values and variability for all analysed parameters were comparable between *Ors* and *San* (Fig. 13).

Median and variability of the productive parameters remained quite stable when considering the effect *soil*. Under rainfed management the median value of yield was 4.6 t ha^{-1} on average, but improved with irrigation (5.3 t ha^{-1}, on average). Median of *GW* and its variability was slightly higher in *5*, but median and *IQR* of *BW* as well as *WF_GW* and *WF_TW* were comparable among remaining soils (Fig. 13).

Table 6
Simulated values of analysed parameters (average of all factor combinations) for baseline (*BAS*), *RCP_4.5* and *RCP_8.5* for Italian and German sites.

Location	Variable	Unit	RCP		
		t ha^{-1}	BAS	4.5	8.5
Germany	Yield_RF	t ha^{-1}	5.93	6.54	6.61
	Yield_IR	t ha^{-1}	7.28	7.98	8.01
	GW	mm	367	371	371
	BW	mm	50	51	51
	WF_GW	m^3 t^{-1}	930	734	716
	WF_TW	m^3 t^{-1}	850	643	631
Italy	Yield_RF	t ha^{-1}	4.39	4.40	4.43
	Yield_IR	t ha^{-1}	5.16	5.22	5.28
	GW	mm	298	289	284
	BW	mm	47	47	49
	WF_GW	m^3 t^{-1}	919	883	880
	WF_TW	m^3 t^{-1}	718	684	673

Table 5
Combinations of crop models, location, soils, GLobal Circulation Model (GCM), Representative CO_2 Concentration Pathways (RCP) and evapotranspiration models (ETP) used in the modelling ensemble.

Location	Soil					GCM						RCP		ETP	
Germany															
Mann	Mub	Flu	Cam	Pod		BAS	BNU	CNRM	HAD	IPSL	MRI	4.5	8.5	PT	PM
A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H		A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	C,D,H	A,H
Location	Soil					GCM						RCP		ETP	
Italy															
Ors	San	1	5	6	8	BAS	BNU	CNRM	HAD	IPSL	MRI	4.5	8.5	PT	PM
A,C,D,H	C,D,H	A,C,D,H	C,D,H	C,D,H	C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	A,C,D,H	C,D,H	A,H

A = Aquacrop; C = Cropsyst; D = DSSAT; H = Hermes; PT = Priestley-Taylor; PM = Penman–Monteith; BAS=Baseline; BNU = Beijing Normal University Earth System Model; CNRM = Centre National de Recherches Météorologiques—Groupe d'études de l'Atmosphère Météorologique; HAD = Hadley Centre Global Environmental Model; IPSL = Institut Pierre Simon Laplace-5th Phase of the Coupled Model, MRI = Global coupled atmosphere-ocean general circulation model; 4.5 = RCP_4.5; 8.5 = RCP_8.5.

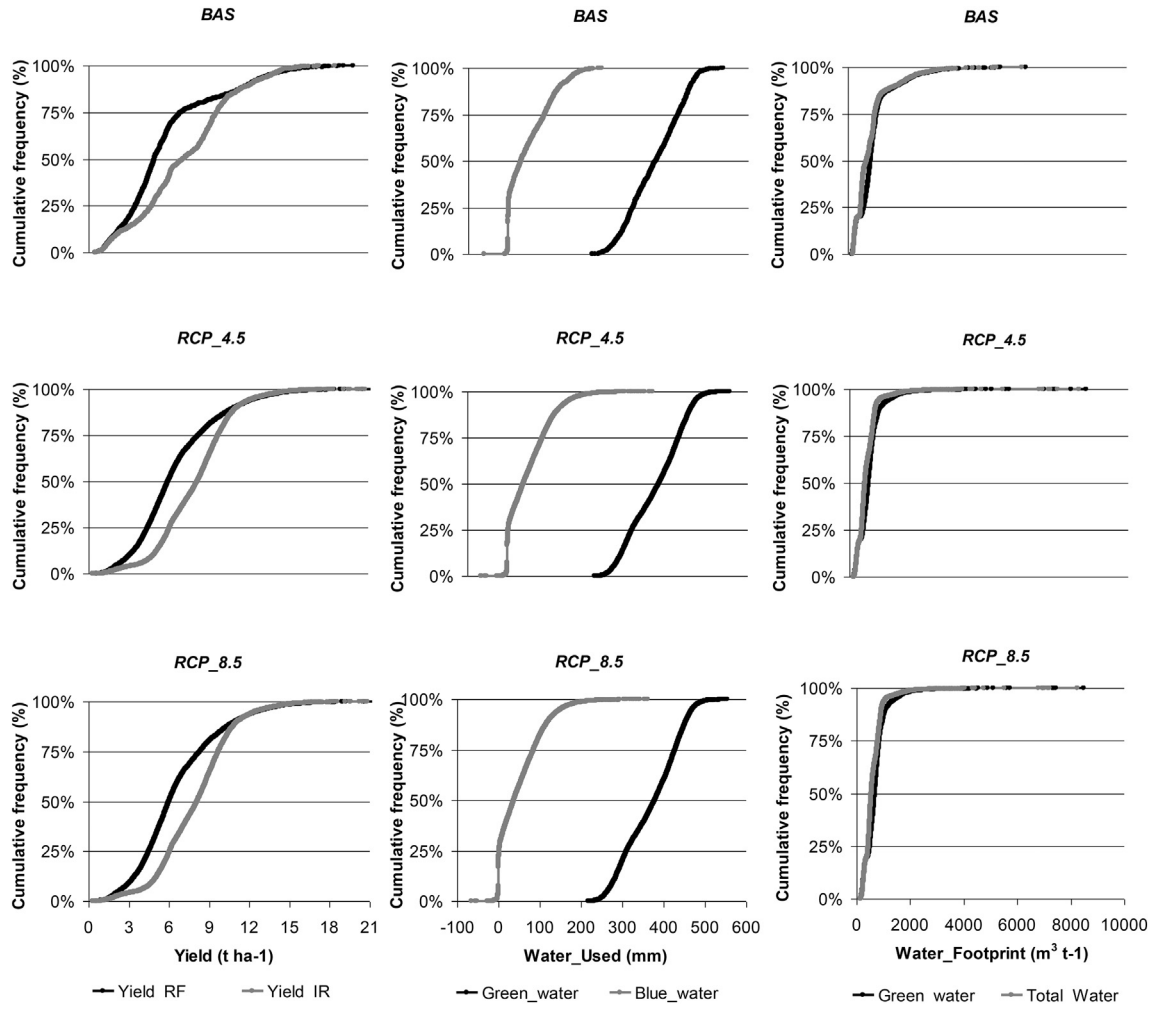

Fig. 6. Cumulative frequency distribution of yield, water use and water footprint in baseline (*BAS*) and future weather scenario (*RCP_4.5* and *RCP_8.5*) in Germany.

Median and *IQR* of parameters was unchanged between *RCP*s, thanks to the process of accommodation of plant to CO_2 alterations, as formalized by the models (Fig. 15).

Estimation of *ETo* with Priestley-Taylor and Penman–Monteith resulted in a high differentiation of the median values for yield and water consumption under rainfed management, according to the evapotranspiration model. Indeed the median score of *Yield_RF* was more than doubled if compared to *Yield_IR*, even if the water supply reduced the gap of wheat productivity between *ETP* models. Despite the median (but not its variability) of *GW* was comparable between models, the water consumption from irrigation was far higher in *PM* with respect to *PT*. As a result, median and *IQR* of *WF_GW* and *WF_TW* were considerably higher in *PM* than *PT* model (Fig. 15).

3.4. Ranking the components of uncertainty

3.4.1. Uncertainty ranking in Germany

Contrasting results were observed from the ranking of analysed factors (Fig. 16). Crop model was the most explanatory factor for yield in rainfed condition, *BW* and *WF_GW*. On the other hand, yield under irrigated management and *WF_TW* were mainly affected by the soil characteristics. However, soil type represented the second main factor for grain yield in rainfed condition, *GW* and *WF_GW*, due to the difference in their texture and hydraulic properties which affected the soil plant available water.

As expected, evapotranspiration model affected primarily the water used by crop stemming from rain infiltrated into soil and secondarily the water supplied with irrigation.

Except for a moderate effect on irrigated crop productivity and *WF_TW*, *GCM*s seemed to have a minor impact on the other factors. This trend underlined an agreement among the global circulation models in predict the level of variations of climatic variables in the future projections.

Excluding the fair weight on grain production under rainfed management, changing in atmospheric CO_2 concentration under *RCP* scenarios did not result in a key factor on ranking the uncertainty. Despite *RCP* was the third explanatory factor for yield under rainfed condition, the effect of CO_2 on the other parameters was masked by other factors (first of all, site characteristics) that mostly affected water consumption, yield and related *WF*.

3.4.2. Uncertainty ranking in Italy

ETP model was the main explanatory factor for yield (rainfed and irrigated), *BW*, *WF_GW* and *WF_TW* (Fig. 17). Crop models had a significant impact on water consumption of rainfed cropping system and secondarily on consumption of irrigation water and related productivity. Under rainfed management, soil type was a fairly significant factor in determining yield, water consumption and productivity, followed by the cultivation site.

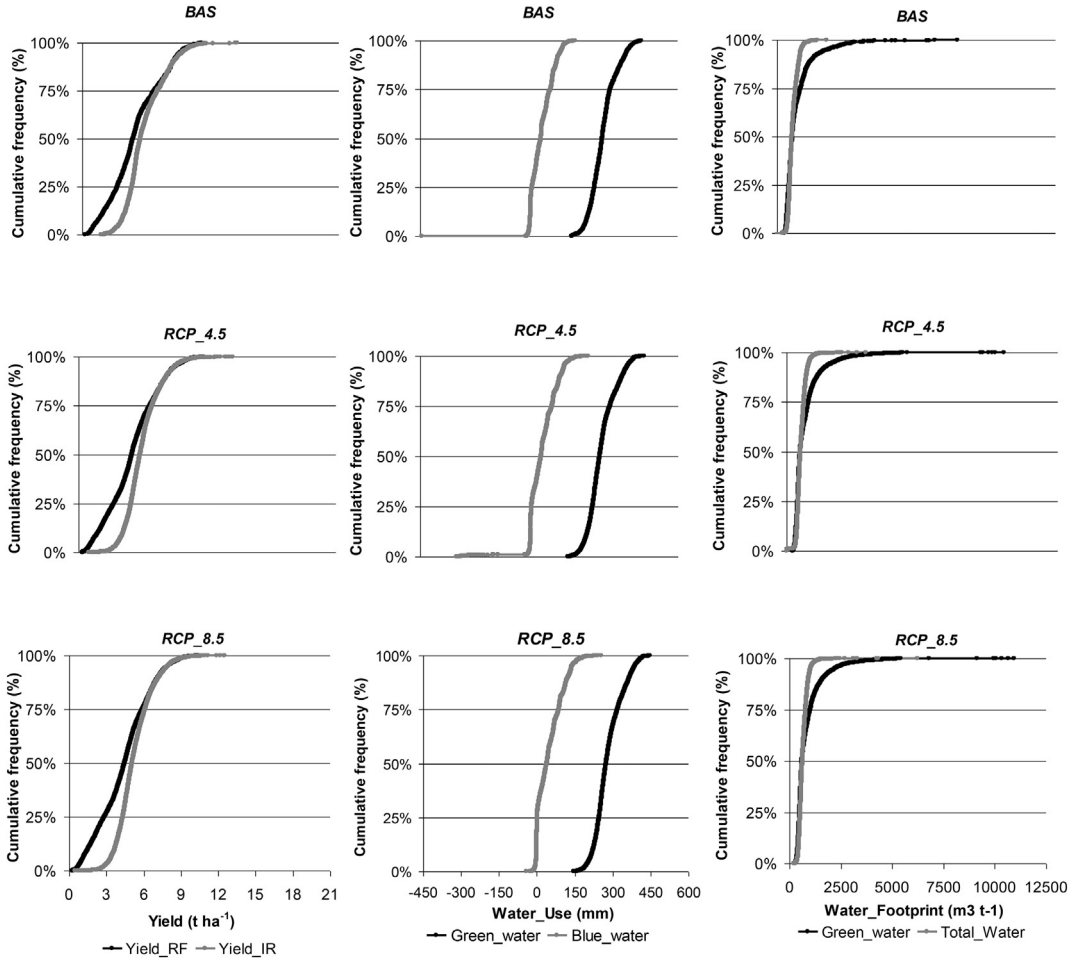

Fig. 7. Cumulative frequency distribution of yield, water use and water footprint in baseline (*BAS*) and future weather scenario (*RCP_4.5* and *RCP_8.5*) in Italy.

Finally, climatic projections (variation in atmospheric CO_2 concentration and weather components) resulted the factors that less impacted on crop performances and water consumption.

4. Discussion

4.1. Future trends: better crop performance, lower water consumption

We assessed the productivity and water consumption of wheat under future climate projections in two different European sites, for providing useful information to stakeholders and policy makers.

Results indicated that under future climatic projections, wheat productivity would remain stable (Italy) or even increase (Germany) by 11% as compared to the current conditions even under rainfed conditions. However, water supply would increase the crop performance with a higher magnitude in the Continental zone (+22% as mean; see German sites) than in the Southern zone (+19%; Italian sites).

An increase in temperature could negatively affect the wheat productivity. Though a huge potential exists for closing the current yields gaps between different regions in Europe (Schils et al., 2018), extreme weather events may still affect cereal yields negatively once certain thresholds are exceeded (e.g. Gobin, 2018). Simulation studies (i.e. Rosenzweig and Tubiello, 1996; Asseng et al., 2013) reported that an increase in temperature during the anthesis-grain filling stage may cause reductions in grain yield of up to 50%. Field trials (Ferris et al., 1998; Barber et al., 2017) corroborated this trend, indicating a reduction up to 20% in grain fertility and up to 50% in grain yield if heat stress occurred during the anthesis-grain filling period.

On the other hand, simulation studies which took into account the effect of increased atmospheric CO_2 concentration on wheat performance, demonstrated that carbon dioxide fertilization counterbalanced the negative effect of raised temperatures. Ventrella et al. (2015) indicated that an increment in atmospheric CO_2 concentration from 360 ppm to 770 ppm in Mediterranean environment, led to a boosting in wheat production of 2.0 t ha^{-1} (2.3 t ha^{-1} with water supply) to 3.1 t ha^{-1} (3.4 with irrigation), also when the cultivation was carried out under an incremented average temperature equal to 5 °C.

In a long simulation study performed with CropSyst, Garofalo and Rinaldi (2013) reported that in the Foggia district, an increment in average temperature of +1 °C during the flowering period and +2.2 °C during the grain filling period caused a shortening of growing cycle of 6 days. However, the transition of atmospheric CO_2 concentration from 358 ppm to 550 ppm ensured a small improvement in grain yield under rainfed condition (2.6 t ha^{-1} vs. 2.7 t ha^{-1}).

Difference in yield and water consumption experienced between Italian and German sites was due to weather trends.

Cumulated rainfall during the growing period was higher (+15% on average) in Germany than in Italy, a percentage that rose up to 50% when considering the flowering-grain filling period. Moreover, the sum of monthly mean temperature was more than double in Italy compared to Germany during the growing period.

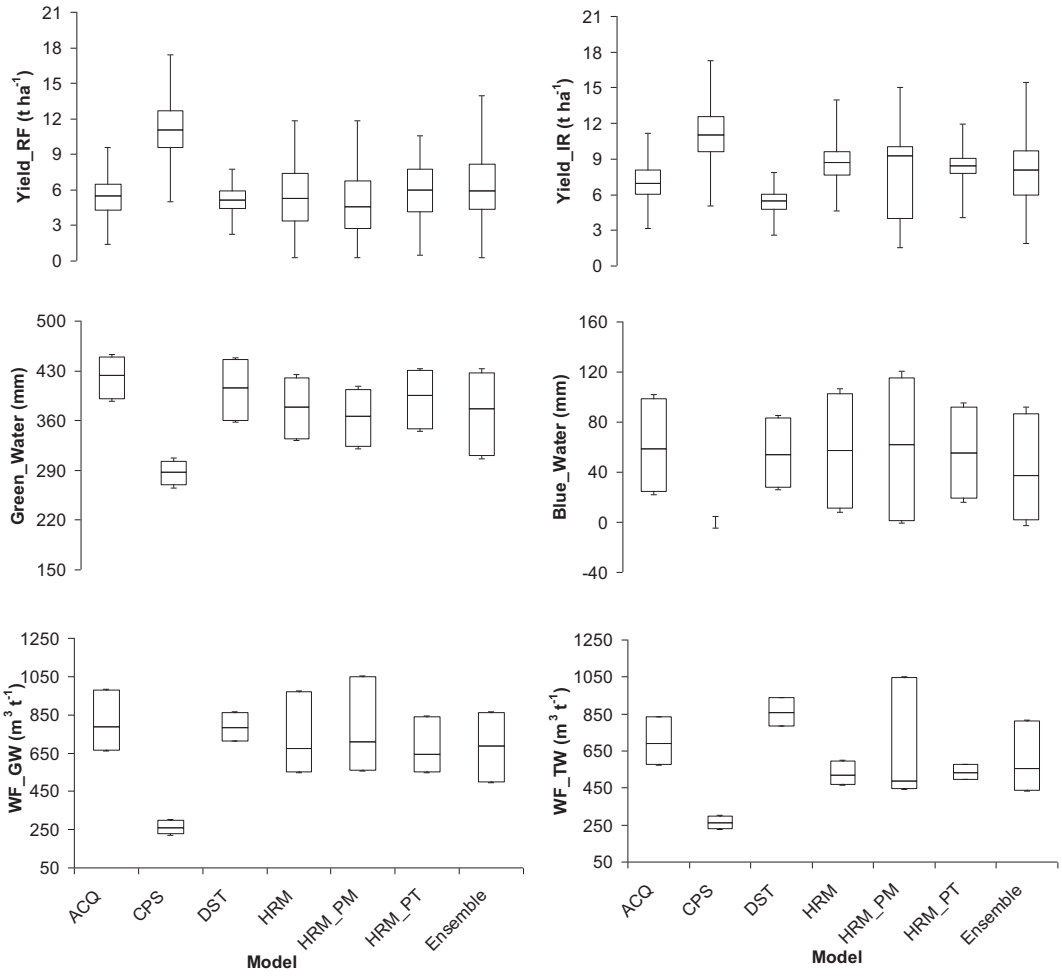

Fig. 8. Boxplots of analysed parameters according to crop models output for Germany. The ends of the whisker are set at 1.5*IQR above the third quartile and 1.5*IQR below the first quartile.

This led to the discussion about differences in water consumption between Italian and German sites. Water consumed by the crop (excluding the effect of irrigation) was determined by the combined effect of water availability (rainfall and soil water storage capacity) and temperature. In Italy, lower *GW* (−69 mm) as compared to Germany can be explained by the shortening of the growing cycle and stomatal closure in response to drought, resulting in a low performance of crop productivity (−1.5 t ha^{-1}). In future climate projections the increment in temperature would determine a higher plant water consumption when the plant available water is not a limiting factor (i.e. for Germany); on the other hand, increased temperature coupled with drought (i.e. for Mediterranean area) would result in a decrement of water loss by evapotranspiration. As reported by Rinaldi et al. (2015), an increment in atmospheric CO_2 concentration improved the gas concentration in intercellular tissues and net photosynthesis rate. This explains the gain in terms of grain yield both in German and Italian sites under the improved atmospheric CO_2 concentration scenarios, also when the soil available water is under the optimal threshold.

Indeed, the positive effect of increased CO_2 concentration on crop performance was evident in *Ors* and *San*, for which a stable yield productivity was simulated also under reduced water consumed by plants under future climate projections.

Consequently, forecasted *WF_GW* would tend to decrease in the Continental region, and remain stable in Mediterranean area, owing to a better water exploitation rather than a lower water requirement (Rinaldi et al., 2015). This statement is also strengthened by the analysis of the irrigation water (amount) used by the crop under future trends in comparison with *BAS*.

The percentage of *BW* in the whole water consumption counting (*WF* + *BW*) was stable to 12% in the German sites and confined to 13–14% in the Italian sites, under the several climate scenarios. This means that the increment in temperature coupled with reduced rainfall does not result in a higher water requirement (supplied with irrigation), thanks to the benefit of improved atmospheric CO_2 concentration on plant performance.

The better the water use efficiency, the lower the demand for water from the crop; this explained the reduced *WF_TW* predicted by the ensemble modelling in future climate projections.

Results discussed so far, came from different plant growth modelling approaches within each simulation model. Indeed, the architecture of *AQC* is based entirely on water consumption and the effect of water stress is modulated by indices whose values are modelled according to the soil water availability; solar radiation does not affect either photosynthesis or crop growth. Differently, crop growth simulation approaches implemented in *HRM* and *DST* rely on the photosynthesis process, driven by solar radiation and modulated by water stress, the latter expressed as a ratio between actual and potential transpiration.

CPS uses two growth engines simultaneously to estimate the plant development, namely: i) biomass accumulation as a function of transpiration use efficiency; and, ii) as a function of radiation use efficiency. The lowest daily value of biomass accumulation is used to estimate the potential biomass. A physical-based approach is used to estimate the

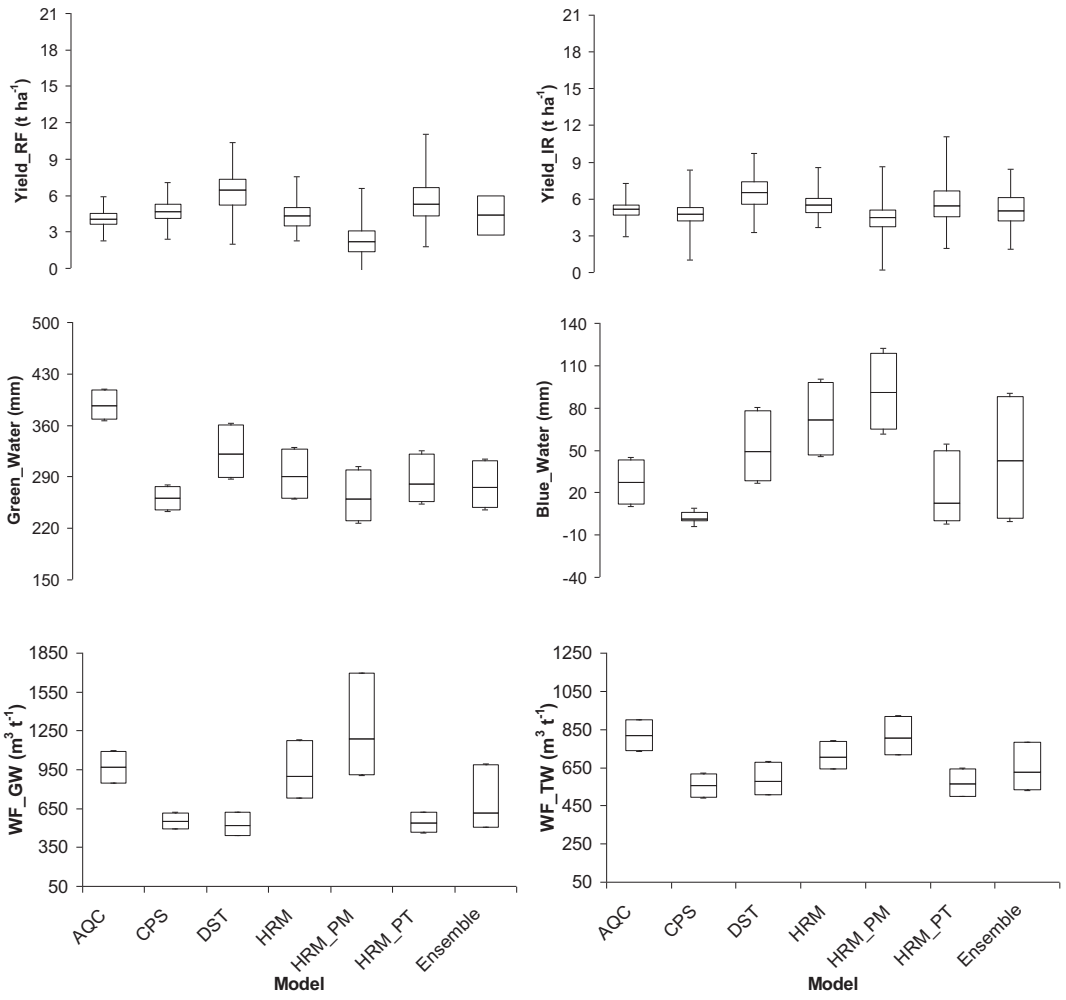

Fig. 9. Boxplots of analysed parameters according to crop models output for Italy. The ends of the whisker are set at 1.5*IQR above the third quartile and 1.5*IQR below the first quartile.

stomatal closure and reduction of water used by the crop, which determines also the actual plant biomass.

The coefficient of variation (*CV*; expressed as ratio between standard deviation and mean) of total water consumption (*BW* + *GW*) among models was 20.8%; this variability was consistent with two other studies investigating wheat productivity and water consumption to climatic change (Kersebaum et al., 2016; Cammarano et al., 2016) within an ensemble of crop models. However, *CV* rose to 59.2% (reduced to 43.1% with irrigation) for grain yield, pointed out as the models differed in approaching the water loss by evapotranspiration and in the formalization of its efficiency (net of water and thermal stress) in grain production.

The crop models involved in this study do not implement any algorithm for the estimation of canopy damage resulting from heat and/or cold waves, so the arguments put forward so far could lead to overestimation of crop growth and/or grain yield.

The different architectures of the models in the formalization of the "atmospheric CO_2 concentration-crop development" link was indicated as a further source of uncertainty in predicting yield under variable levels of carbon dioxide fertilization (Kersebaum and Nendel, 2014; Li et al., 2015). *DST* uses a set of algorithms that act on the net photosynthesis rate by adjusting the radiation use efficiency as a function of atmospheric CO_2 concentration and afterwards transpiration use efficiency; *HRM* uses a non-linear CO_2-gross photosynthesis response that affect on stomatal resistance and CO_2, assimilation rate as a function of vapour pressure deficit. In *CPS*, variations of atmospheric CO_2 concentration module transpiration and radiation use efficiency by means of a ratio calculated after fitting a nonrectangular hyperbola. In *AQC* the water productivity increases linearly under CO_2 enrichment by a coefficient that considers the difference between a reference value and the atmospheric concentration.

Despite the different algorithms used in the modelling of plant-CO_2 response, the simulated data were comparable among models, at least in the range of atmospheric CO_2 concentration set up in this study. However, the empirical approach used by the crop models was certainly a limitation if compared to photosynthesis process-based models (i.e. Farquhar-type model; Farquhar et al., 1980; Farquhar and von Caemmerer, 1982; Garofalo et al., 2014).

Finally, significant differences in wheat productivity were simulated between the two areas under study. This was due to the high climatic heterogeneity between locations, observing for the Italian district higher average temperatures and more severe drought conditions compared to the German sites, both for the current conditions and future climate projections.

4.2. Factors of uncertainty

Interesting results emerged when analyzing the rank of the factors underlying the model predictions, which is a fundamental step to provide reliable information to stakeholders and policy makers (Ruiz-Ramos and Minguez, 2010). Analyzing and ranking the factors of

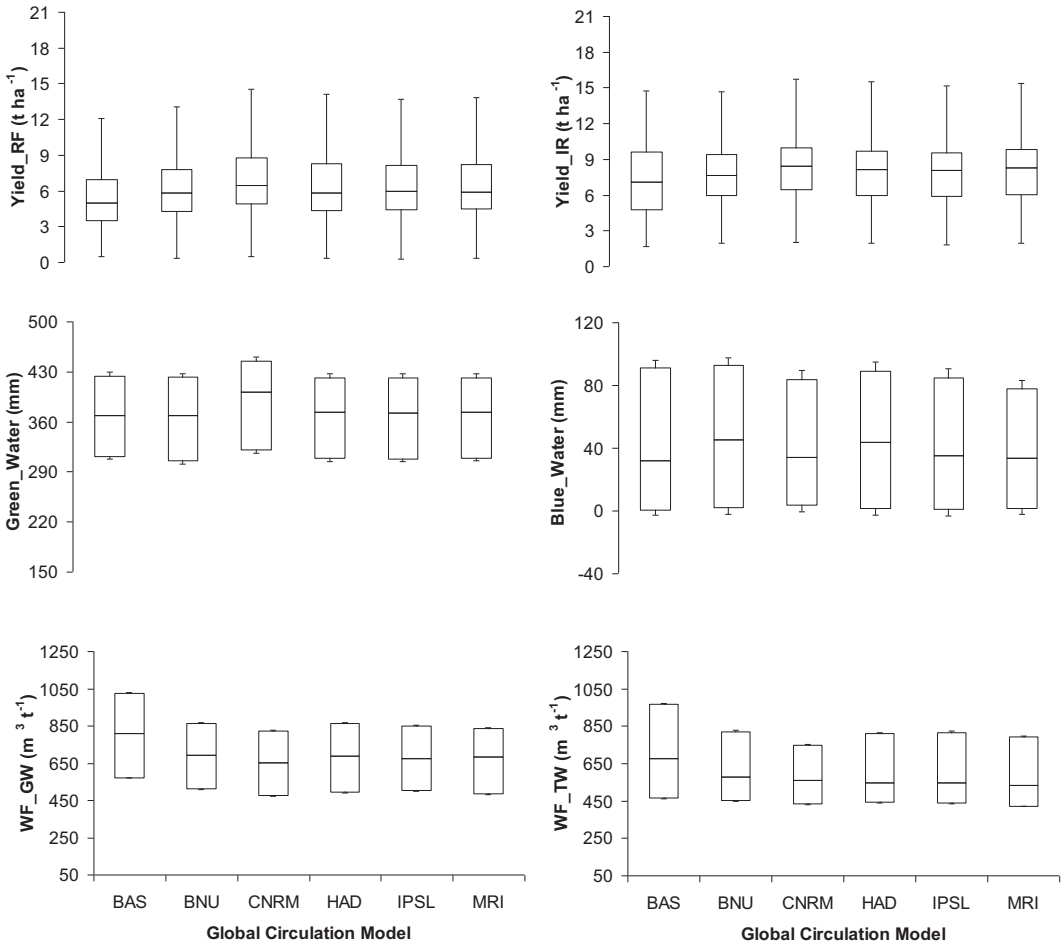

Fig. 10. Boxplots of analysed parameters according to *GCMs* output for Germany. The ends of the whisker are set at 1.5**IQR* above the third quartile and 1.5**IQR* below the first quartile.

uncertainty, two key points emerged clearly: i) locations (Continental area vs. Mediterranean area), which heavily affected the rank of each factor; ii) the weight of a factor, *in casu* the *ETP* model, that is usually not considered in the ensemble modelling studies and therefore, can be considered as a "hidden factor". The main source of variability in rice (Bregaglio et al., 2017) and wheat (Olesen et al., 2007) yield prediction was the location under similar climatic pattern; in this context the soil characteristics can play a major role in determining yield, water consumption (Kersebaum and Nendel, 2014; De Frutos Cachorro et al., 2018) and water footprint, especially under rainfed conditions (as assessed in our study). The rank of "crop model" and "*RCP* scenario" factors underlined the different sensitivity of the models in simulating yield, water consumption and related *WF* according to different climatic patterns, soil water balance and atmospheric CO_2 concentration. Our results demonstrated the importance of the factor "model" on quantifying the wheat productivity, *BW* and *WF_GW* as a consequence of changed weather scenarios in Continental sites, similarly to Aggarwal and Mall (2002) and Matthews et al. (1997). On the other hand, the weight of this factor became important in assessing yield under irrigation management, water consumption (both *GW* and *BW*) and water footprint for Italian sites. In addition, the poor contribution of *RCP*s, at least for the near future in the uncertainty of future predictions (especially in the Mediterranean area), could lead to two different arguments: i) a low sensitivity of the empirical approaches implemented in the models in simulating the plant response to different atmospheric CO_2 concentrations in the range explored in this study (360–550 ppm); ii) the compensatory effect of increased CO_2 with respect to other weather variables that could compromise wheat performance in future climate scenarios.

As mentioned earlier, the *ETP* model proved to be a factor with a substantial weight on the uncertainty of output not previously expected. Especially in Mediterranean area, the main contributor to the uncertainty of the analysed parameters (excepting for *GW*) was the evapotranspiration modelling approach. Lower yield production (mitigated with irrigation), lower green water consumption (although no so dramatic) and a higher demand for blue water indicated higher values of *ETo* estimated with *PT* model compared to that of *PM*. The higher water demand and higher water loss by evapotranspiration of *PT* than *PM* approach was found out in experimental trials carried out by Utset et al. (2004) in the Mediterranean environment. Therefore the screening of different *ETP* algorithms, within the ensemble of crop models, is an important key point when assessing the demand, supply and loss of water by crops in drought or in changed climate conditions.

5. Conclusion

The ensemble of crop models highlighted that wheat production would not be compromised in the Mediterranean environment and even improved in the Continental area in future climate scenarios, also under rainfed management. However, higher grain yield did not correspond to a higher water consumption due to the positive effect of CO_2

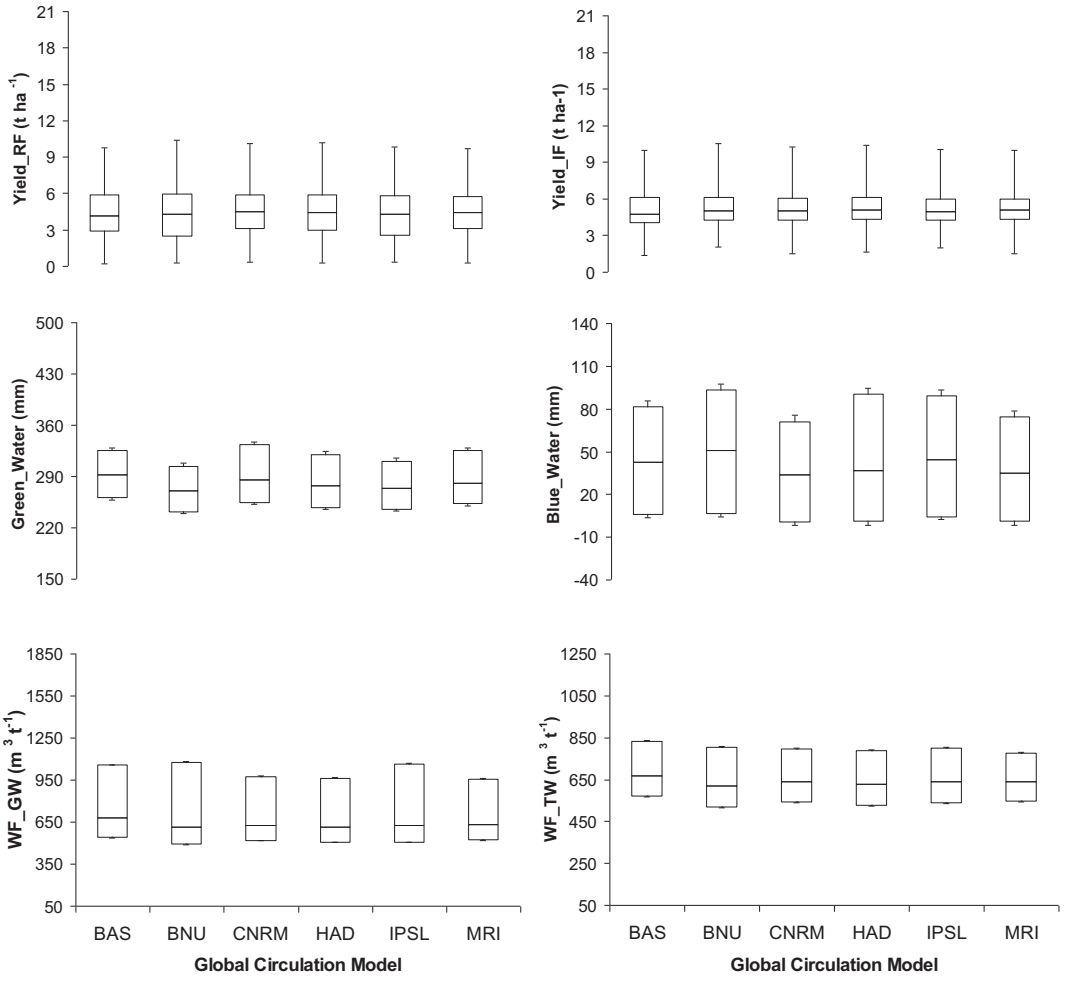

Fig. 11. Boxplots of analysed parameters according to *GCMs* output for Italy. The ends of the whisker are set at 1.5**IQR* above the third quartile and 1.5**IQR* below the first quartile.

fertilization on the main crop parameters that affected the plant growth and development, i.e. *Temperature and Radiation Use Efficiency* and *RUE*. In Northern countries and depending on the soil, wheat could take advantage from irrigation, even with water supply equal to 50% of water depletion, whereas in Mediterranean countries additional water supply would not entail substantial improvement of the grain yield.

However, the ensemble of models pointed out how in future projections *WF* would decrease, due to an improved efficiency of plants to process the water in grain.

In summary, our study indicated that the European wheat production sector has the potential to improve the current yield levels and take advantage of atmospheric CO_2 fertilization; a further boost would derive from irrigation, but the economic benefit of such practice does not seem adequate to justify the water supply (Ventrella et al., 2015; De Frutos Cachorro et al., 2018).

Further investigations are needed to explore a wider range of future climate scenarios, atmospheric CO_2 concentration, crop simulation models and evapotranspiration approaches in other climatic areas of Europe. Adaptation strategies or diversified cropping systems can be processed in simulation exercises to assess their mitigation effect in response to climate extremes in other pedo-climatic contexts.

CRediT authorship contribution statement

Pasquale Garofalo: Software, Formal analysis, Writing - original draft, Writing - review & editing. **Domenico Ventrella:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision. **Kurt Christian Kersebaum:** Conceptualization, Methodology, Software, Writing - review & editing. **Anne Gobin:** Software, Writing - review & editing. **Miroslav Trnka:** Writing - review & editing. **Luisa Giglio:** Software, Writing - review & editing. **Martin Dubrovský:** Resources, Writing - review & editing. **Mirko Castellini:** Formal analysis, Writing - review & editing.

CRediT authorship contribution statement

Pasquale Garofalo: Software, Formal analysis, Writing - original draft, Writing - review & editing. **Domenico Ventrella:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision. **Kurt Christian Kersebaum:** Conceptualization, Methodology, Software, Writing - review & editing. **Anne Gobin:** Software, Writing - review & editing. **Miroslav Trnka:** Writing - review & editing. **Luisa Giglio:** Software, Writing - review & editing. **Martin Dubrovský:** Resources, Writing - review & editing. **Mirko Castellini:** Formal analysis, Writing - review & editing.

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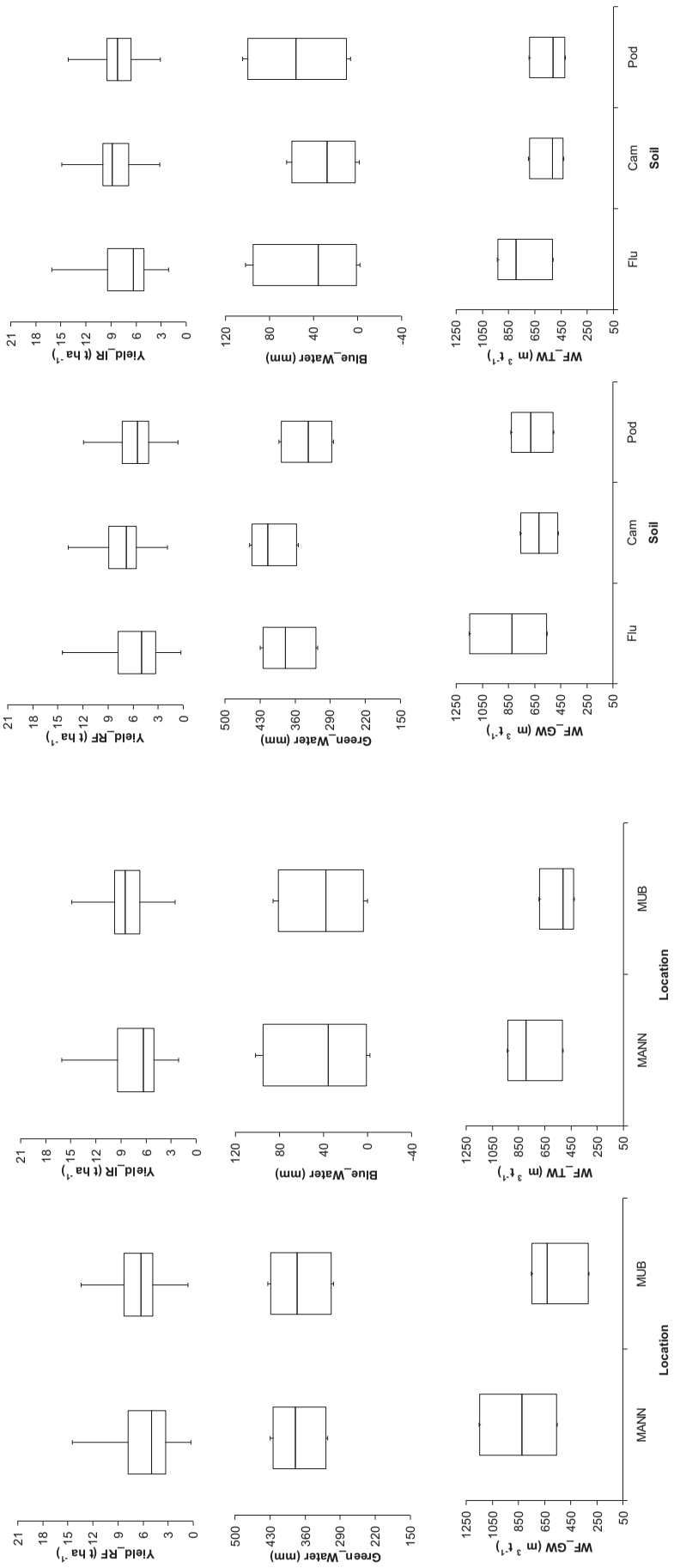

Fig. 12. Boxplots of analysed parameters according to locations and soils output for Germany. The ends of the whisker are set at 1.5*IQR above the third quartile and 1.5*IQR below the first quartile.

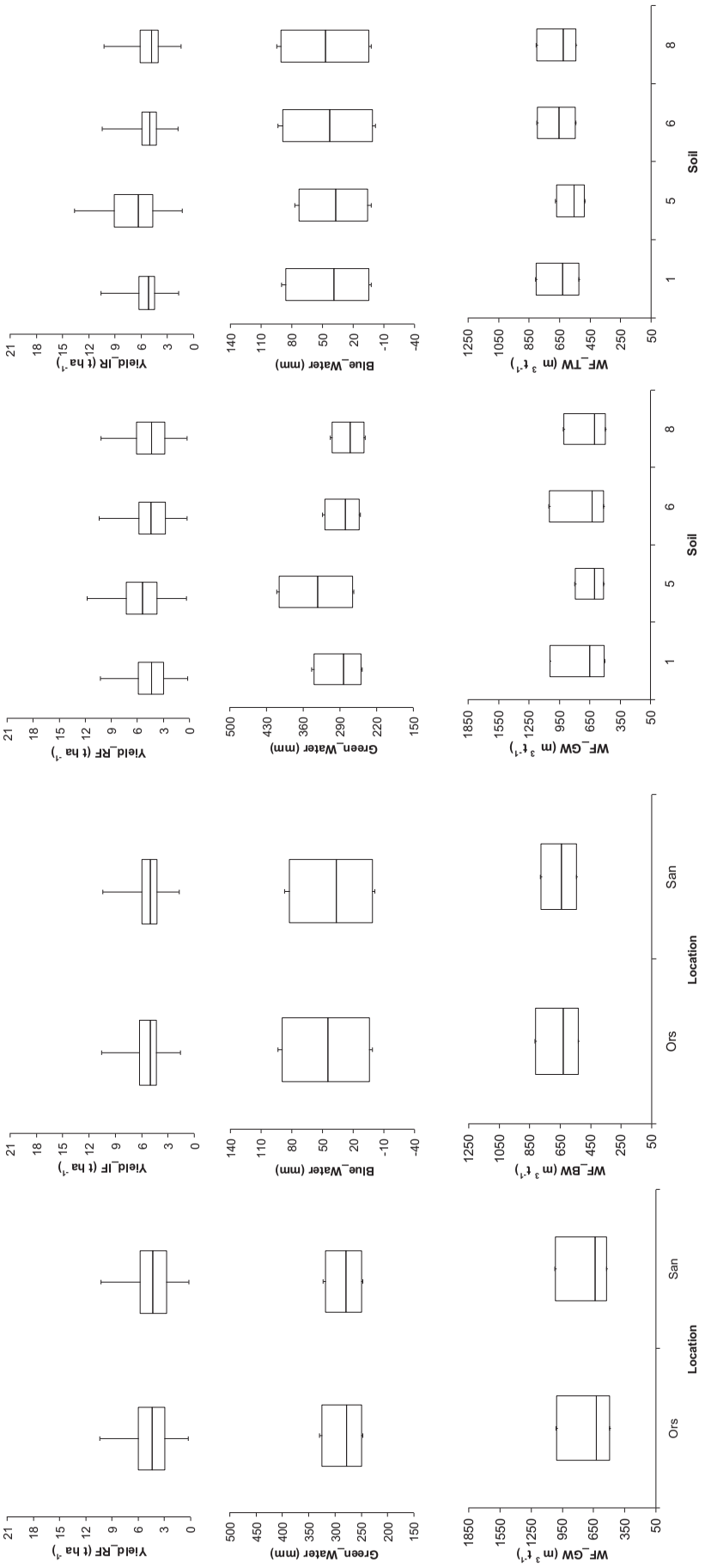

Fig. 13. Boxplots of analysed parameters according to locations and soils output for Italy. The ends of the whisker are set at 1.5*IQR above the third quartile and 1.5*IQR below the first quartile.

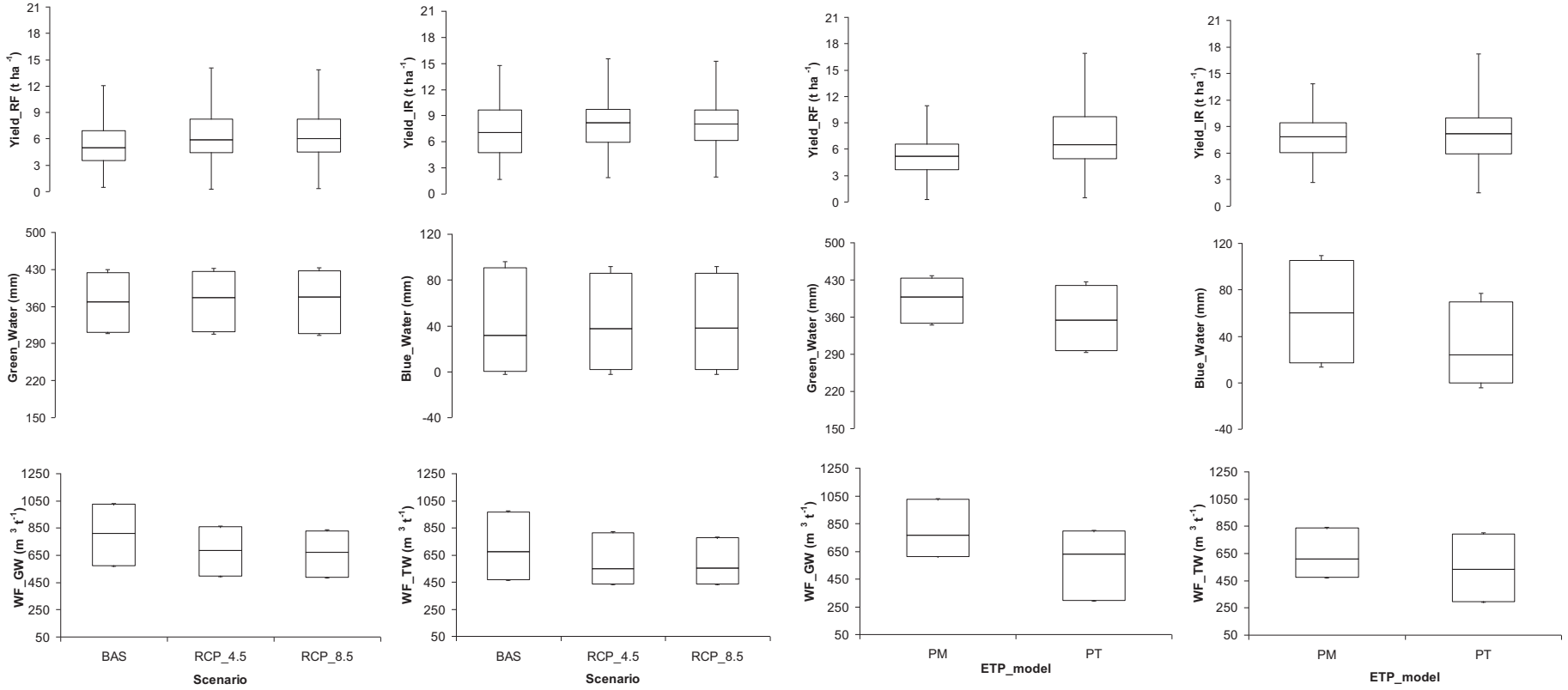

Fig. 14. Boxplots of analysed parameters according to Representative CO_2 Concentration Pathway (*RCP*) scenarios and *ETP* model output for Germany. The ends of the whisker are set at 1.5*IQR above the third quartile and 1.5*IQR below the first quartile.

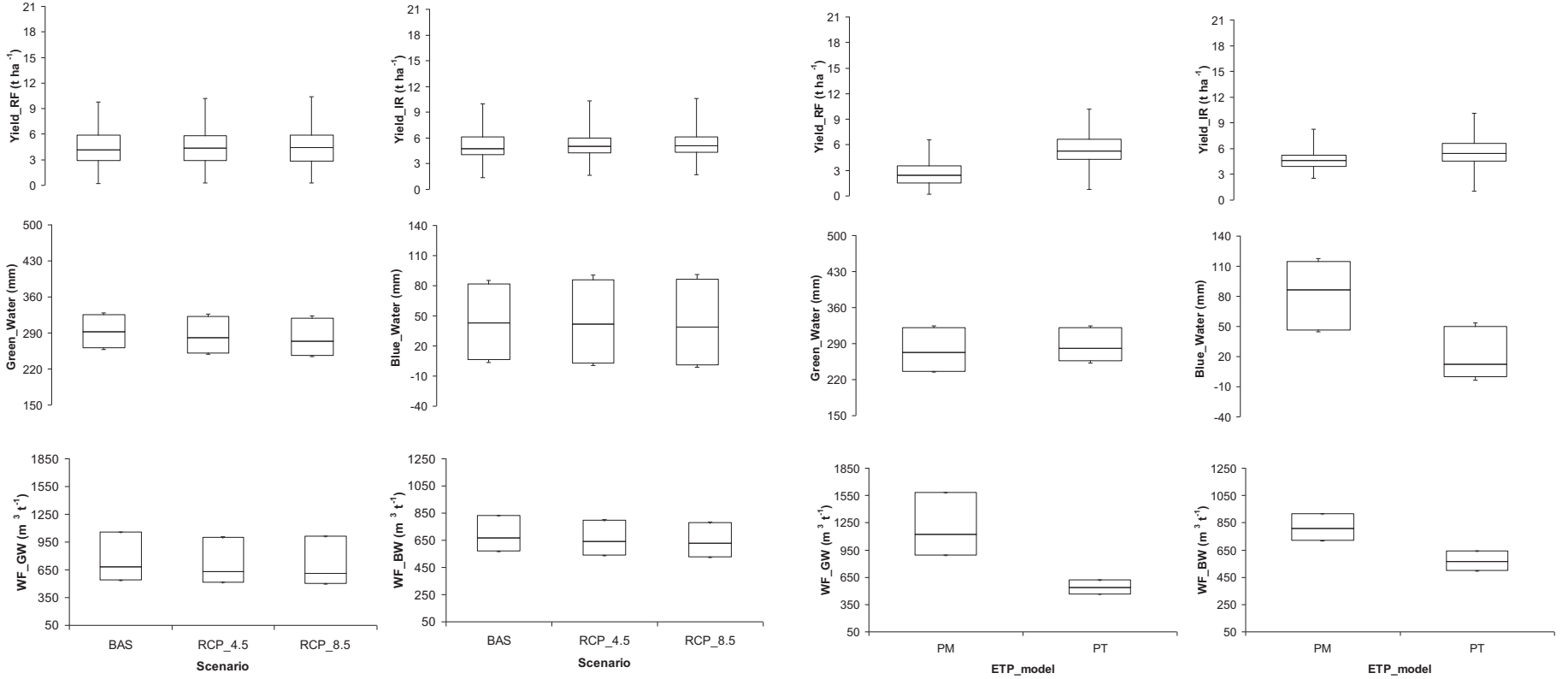

Fig. 15. Boxplots of analysed parameters according to Representative CO_2 Concentration Pathway (*RCP*) scenarios and ETP model output for Italy. The ends of the whisker are set at 1.5**IQR* above the third quartile and 1.5**IQR* below the first quartile.

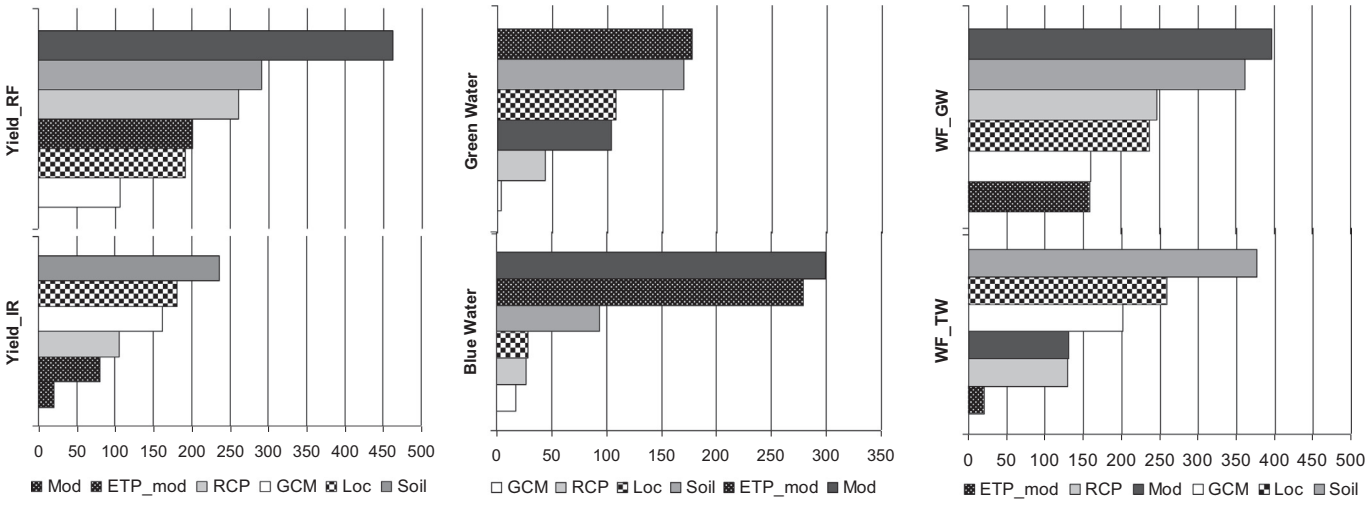
Yield_RF
Yield_IR
0 50 100 150 200 250 300 350 400 450 500
Mod ETP_mod RCP GCM Loc Soil
Green Water
Blue Water
0 50 100 150 200 250 300 350
GCM RCP Loc Soil ETP_mod Mod
WF_GW
WF_TW
0 50 100 150 200 250 300 350 400 450 500
ETP_mod RCP Mod GCM Loc Soil

Fig. 16. Weight of the different effects on analysed parameters in Germany. Bars represent the absolute value of the difference between the mean of the rank of each factor and the total average.

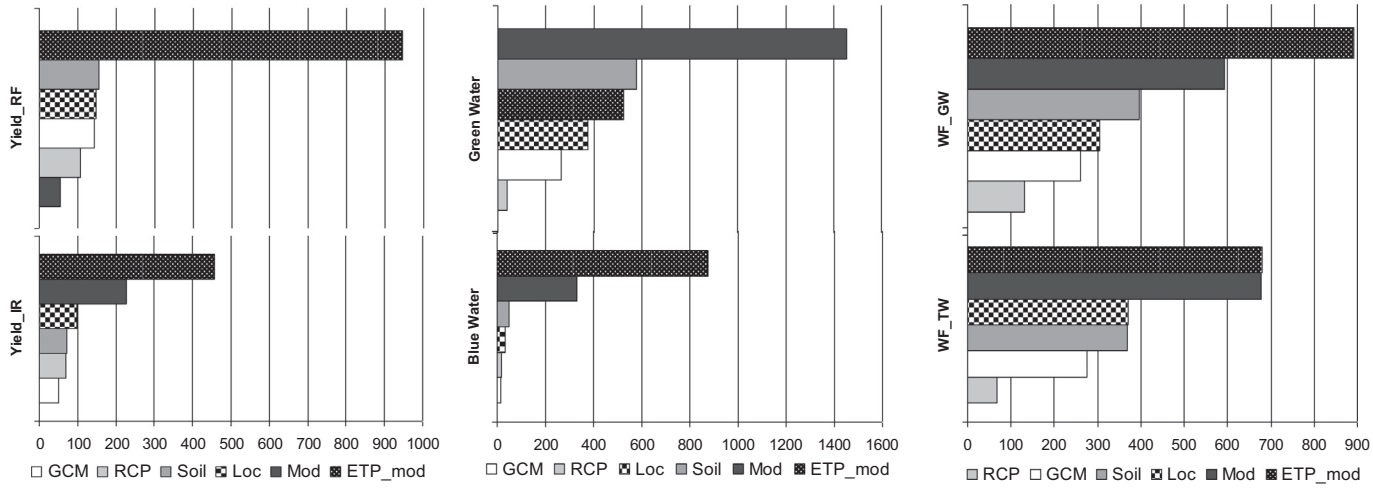
Yield_RF
Yield_IR
0 100 200 300 400 500 600 700 800 900 1000
GCM RCP Soil Loc Mod ETP_mod
Green Water
Blue Water
0 200 400 600 800 1000 1200 1400 1600
GCM RCP Loc Soil Mod ETP_mod
WF_GW
WF_TW
0 100 200 300 400 500 600 700 800 900
RCP GCM Soil Loc Mod ETP_mod

Fig. 17. Weight of the different effects on analysed parameters in Italy. Bars represent the absolute value of the difference between the mean of the rank of each factor and the total average.

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